5

THE BASALTS AND GRANITIC ROCKS OF THE BALLARAT DISTRICT

By H. Yates, M.Sc.

[Read 9 July 1953]

Contents

Introduction

The field observations and laboratory work on which this paper is based were made over a period of more than ten years, with the assistance of an expenses grant from the University of Melbourne during part of this time.

The whole district was geologically surveyed by the pioneers of the Geological Survey of Victoria, and the outcrops of the basalts and granitic rocks are shown on the map of the Alluvial and Deep Lead Systems (Hunter, 1909, plate 4). However, no detailed descriptions of the igneous rocks have as yet been published, although chemical analyses and thin sections of some of them were made in the laboratories of the Department of Mines.

Chemical analyses of 47 basalts and also 16 granitic rocks and minerals were made by the author in the Geology laboratory of the School of Mines, Ballarat.

I wish to thank Ex-Professor H. S. Summers, Professor E. S. Hills, Mr. G. Baker, Dr. A. B. Edwards, and Mr. W. Baragwanath for valued advice and assistance during the preparation of the paper.

Part I.—Petrology of the Basalts and Tuffs

At several places in the Ballarat district sections of Cainozoic basalts or basalts and tuffs occur, comprising at least two distinct lava flows, although in some cases all the rocks of the sections are not exposed at the surface. Thus at Ballarat West, Smeaton and other places, diamond drill boring to determine the course of the deep leads, and also shaft sinking during the mining operations, have proved the existence of four or more basalt sheets, while basalt blocks included in the outcropping tuff beds at Burrumbeet indicate the presence of several flows beneath the surface there.

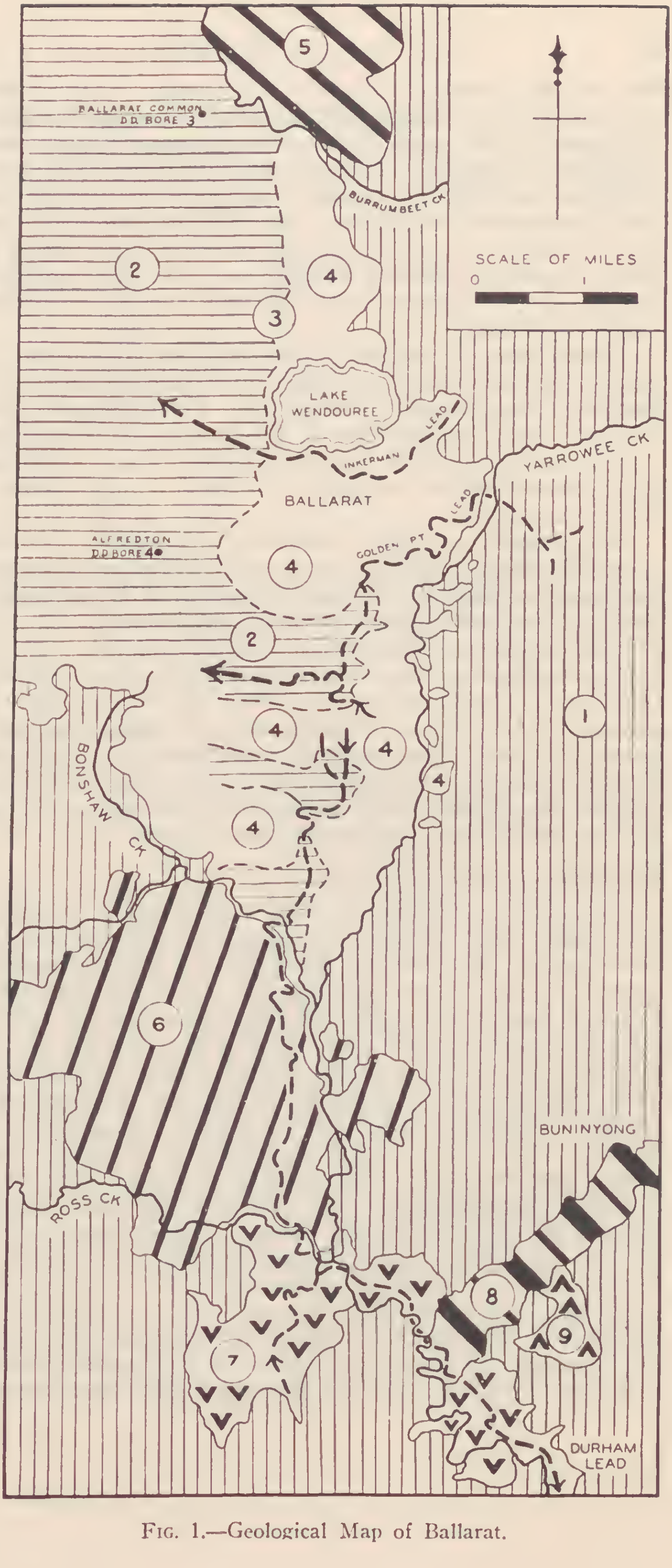
The main object of the work done was to place on record the author's chemical analyses of the basalts in the Ballarat district, and the evidence they give of differentiation in the basaltic magma before extrusion, during the inter-eruptive periods, and in the individual lava sheets after extrusion. The conclusions arrived at depend on the assumption that the various associated basalt sheets in each area were co-magmatic, and this seems justified by their limited extent and the brevity of the inter-eruptive periods as shown by the absence of thick deposits of sedimentary origin between successive sheets. One exception is the Ballarat West area, where the interbasaltic clays are up to 60 ft. thick in places, but it is probable that deposition in river lakes was rapid in this case.

In certain areas, such as Smeaton, where the several basalts were obviously extruded from different vents, though quite close together, the possibility of variable cupola differentiation must be considered, so that comparison of the rocks may lead to unreliable conclusions. This is illustrated near Ballarat where very variable alkali content of the basalts has been found within a small area comprising Ballarat West, Mt. Rowan and Warrenheip; however, in this case the different basalts do not come into the same section.

1. Basalts of the Ballarat West Area

In his work *The Ballarat Gold Field,* Baragwanath (1923, p. 51) described the extent and thickness of the basalts encountered in the mining shafts. In his first reference to them he states that there are four distinct layers, but later (p. 82) when describing the City of Ballarat Mine a fifth layer is mentioned. Actually, this is the oldest and lowest layer, being met at a depth of 367 ft. and penetrated for 30 ft. However, as it was separated from the next overlying basalt by only 5 ft. of cemented drift in the shaft, there seems some doubt as to whether it represents a distinct flow or not. Unfortunately no specimens from the shaft are available for comparison. Four distinct basalt rocks, separated by clays, were also encountered in several other shafts in the western and southern parts of the Ballarat plateau, and were shown in section by Baragwanath. The typical section showing the Ballarat deep leads is well known. Baragwanath made only very brief references to the lithological character of these basalts, but petrological descriptions of the bore cores preserved in the Geological Museum of the Department of Mines, Melbourne, have now been made and are tabulated below.

In the mining days the Ballarat West basalts were named "first rock", "second rock", etc., from the surface downwards; that is, in the order they were met in the shafts and bores. Baragwanath did not consider it necessary to alter this nomenclature, but for the purpose of the present paper the names must be reversed to correspond with the correct order of extrusion, which is more important. From the records of mine shafts it is clear that the first (oldest) and second flows are confined to the valleys of the deep leads. Their approximate extent beneath the younger sheets is indicated on the map (Fig. 1). These early flows probably issued from several separate vents because they partly filled the valleys of the Inkerman Lead, the Golden Point Lead, including the westerly extension towards Cardigan,



1. Ordovician.
2. 1st and 2nd basalts of Ballarat West, underlying the 3rd and 4th flows.
3. Approx. eastern boundary of basalts 1 and 2.
4. 4th basalt underlain by 3rd flow.
5. Mt. Rowan basalt.
6. Cambrian Hill basalt.
7. Napoleon and Durham Lead basalt.
8. Buninyong basalt.
9. Grenville Hill basalt.

FIG. 1.—Geological Map of Ballarat.

and also the Sebastopol Lead in the vicinity of the Prince of Wales mines, but were not found on the shallow ground between these leads. The third and fourth (youngest) flows issued from vents disposed along a meridional fissure in the north-west of the area. This is indicated by a low north-south ridge west of Alfredton and two low hillocks north-west of Lake Wendouree. Flowing more freely as extensive sheets they covered practically the whole of the Ballarat West and Sebastopol area, forming successive volcanic plains which sloped east and south at average gradients of 50 ft. per mile. The present surface slope indicates that the last lava sheet also flowed northwards to Burrumbeet Creek and westwards to Cardigan.

These basalts of Ballarat West terminate at Bonshaw Creek in the south, but beyond this, separate extrusions of basaltic lava occurred at Cambrian Hill and Napoleon along the same fissure line. No prominent cones were built up in the Ballarat West area like those of Mt. Rowan, Mt. Pisgah, etc., to the north.

The first three flows were each found to have a maximum thickness of about 90 ft., while the last ranges up to 160 ft. in the vicinity of its source west of Lake Wendouree.

In addition to surface outcrops, examination has been made of the core specimens from two D.D. bores in this area, one located south of Burrumbeet Creek on the Ballarat Common 2½ miles N.N.W. of Lake Wendouree, being bore No. 3 of the series drilled in 1890; the other is No. 4 of the Alfredton series (1891) located 1½ miles south-west of the lake.

The depth from which the core specimens were taken were not recorded, but they are numbered in sequence from the surface downwards. The number of specimens (15) taken to the bottom of the basalts suggests an average interval of about 20 ft., while the record of interbasaltic clays in the bore logs determines the flow to which any particular core specimen belongs. These two bore cores were selected for special study because the specimens are numerous and obviously include several from each of the basalt sheets.

Correlation of the Two Bores

The hand specimens and thin sections of the corresponding flows in the two bores agree fairly closely; so also do their chemical analyses, except for the effect of the higher H_2O and CO_2 content of the first and second flows of the Alfredton series. However, core specimen No. 11 in the Ballarat Common bore is very different, both lithologically and chemically, from Nos. 10 and 13, and may represent a separate thin flow from a different vent along the fissure. The bore details (Tables 1, 3) taken from the Annual Report of the Secretary for Mines (1890, 1892) and also the descriptions of the core specimens (Tables 2, 4) show the number of different basalt sheets in each case and how they correspond. Thus the first flow is represented by specimens 16 (Alf.) and 14 (B.C.); both are dense, fine-grained blue basalts with a black glassy base. The second flow at Alfredton (specimens 10-15) is a coarse ophitic olivine basalt which varies very little in the six samples and resembles specimens 13 and 10 of the B.C. series. It does not agree at all with Baragwanath's description "obsidian basalt" given for the "third rock" in the shaft details of the City of Ballarat mine. The three specimens 10, 11, 13 in the Ballarat Common bore correspond in depth with the second flow at Alfredton, and as they aggregate only 76 ft. in thickness and are not separated by clays, they are to be considered as a single sheet, despite the difference noted in No. 11. The third flow, specimens 3-9 (Alf.), is a dense

TABLE 1

Details of Ballarat Common D.D. Bore No. 3

Rocks pierced	Depth where struck	Thickness	Thickness of basalt sheets	Number of flow
Soil	0	8′		
Bronw vesicular basalt ..	8′	9′		
Grey basalt	17′	12′	84′ 6″	4
Blue basalt	29′	42′ 6″		
Red vesicular basalt	71′ 6″	13′		
Red clay	84′ 6″	6′		
Grey basalt	90′ 6″	15′ 6″	70′	3
Blue basalt	106′	48′ 6″		
Clays	154′ 6″	35′		
Grey and blue basalt	189′ 6″	76′ 6″	76′ 6″	2
Clay	266′	8′		
Hard blue basalt, vesicular in parts	274′	46′	46′	1
Clay and then bedrock	320′			

fine-grained blue basalt with ophitic texture in most sections. The corresponding rock in the B.C. bore (specimens 4, 5) is dark brown, due to abundant iddingsite, but it resembles the Alfredton sheet texturally and also chemically except for high Fe_2O_3 due to the iddingsite. The top rock of both bores is coarse-grained and dark brownish-grey near the surface (spec. 1) but finer grained towards the base (spec. 2).

Chemical analyses of the principal specimens preserved from the two bores are given in Tabels 5 and 6. The appreciable composition variation from flow to flow shows that differentiation of the magma took place during the interruptive periods. Comparing analysis I with the series II, III, IV (Table 6), it is evident that the first and second basalts in Ballarat West have practically the same composition despite their dissimilarity in hand specimens. Their chief chemical feature is low MgO. It is suggested, therefore, that before the commencement of vulcanicity in this area, differentiation of the magma took place, involving crystallization and sinking of olivine, so that the early lavas were impoverished in this mineral as compared with the later flows (analyses V-VIII).

In the case of the Alfredton bore, three analyses were made of each of the second and third sheets at different depths, in the hope that some definite indication of the trend of differentiation in thick lava flows might be found. However, the three analyses of the same sheet in each case are so nearly the same that we may conclude that the extent of differentiation in basaltic lava sheets up to 100 ft. in thickness, after extrusion, is negligible. The small amount of variation found does not justify the drawing of variation diagrams.

The basalts of Ballarat West are olivine-bearing basic-andesine or labradorite varieties. All the analyses by the present writer show fairly constant and low average totals of combined alkalis ($Na_2O + K_2O$) and in this respect the rocks differ from many other basalts of the district. Other chemical features worthy of note are:

(1) High Fe_2O_3 in the rocks of the Ballarat Common bore, excepting the hard fine-grained bottom rock.

(2) Lower MgO content in the earlier flows of both bore series.

TABLE 2

Description of the Core Specimens, Ballarat Common D.D. Bore No. 3

No. of core specimen	No. of flow	No. of Chem. Analysis	Macroscopical features	Microscopical features
1	4	V	Brown-black, coarse-grained	Olivine iddingsite basalt, doleritic texture. Plagioclase laths large, but augite grains small.
2	4		Brown, finer grained	
4	3		Brown-black, fine-grained but crystalline	
5	3	IV		Ophitic olivine iddingsite basalt
7	—	—	Clays from 170 ft. depth	
8	—	—		
10	2	III	Brown rock, coarse-grained, soft	Ophitic olivine iddingsite basalt
11	2	II	Blue rock, fine-grained vesicular	Fine-grained basalt with dark base, little olivine
13	2		Brown rock, crystalline	Coarse, ophitic olivine basalt
14	1	I	Blue, fine-grained, very hard	Olivine basalt with dark, glassy base

TABLE 3

Details of Alfredton D.D. Bore No. 4

Rocks pierced	Depth where struck	Thickness	Thickness of basalt sheets	Number of flow
Clay	0	9′		
Grey basalt	9′	3′		
Jointy grey honeycomb basalt	12′	26′ 10″		
Decomposed basalt	38′ 10″	4′		
Hard blue basalt	42′ 10″	44′ 1″	167′ 9″	4
Brown honeycomb and grey basalt	86′ 11″	27′ 8″		
Blue honeycomb and grey basalt	114′ 7″	7′ 11″		
Hard blue honeycomb and blue basalt	122′ 6″	45′ 3″		
Fine drift	167′ 9″	1′ 11″		
Grey clay and decomposed basalt	169′ 8″	1′ 3″		
Basalt	170′ 11″	3′ 10″		
Grey and honeycomb basalt ..	174′ 9″	18′ 9″	86′ 10″	3
Blue and honeycomb basalt ..	193′ 6″	47′		
Grey and blue honeycomb basalt	240′ 6″	16′		
Hard clay	256′ 6″	1′ 6″		
Grey, blue and honeycomb basalt	258′	89′ 9″	91′ 3″	2
Basaltic clay	347′ 9″	16′ 9″		
Honeycomb grey and blue basalt	364′ 6″	52′ 6″	69′ 3″	1
Clay and then wash	417′			

TABLE 4

Description of Core Specimens, Alfredton D.D. Bore No. 4

No. of core specimen	No. of flow	No. of Chem. Analysis	Macroscopical features	Microscopical features
1	4		Dark brown, coarse-grained	Coarse olivine-iddingsite basalt
2		VIII	Brown-black, finer grained	Medium-grained olivine-iddingsite basalt
3	3	VII	Blue, fine-grained	Olivine basalt with dark glassy base. Olivine is fresh.
4		VI	Blue, fine-grained	Ophitic olivine basalt with small amount of dark base
8		V	Blue, fine-grained	Olivine basalt with dark base
9			Blue, fine-grained	
10	2	IV	Brown-grey, crystalline	Iddingsitized olivine basalt. Medium-grained, subophitic texture.
11			Brown-grey, crystalline	Secondary carbonates and hyalite present.
12		III	Brown-grey, crystalline	”
13			Brown-grey, crystalline	
14			Brown-grey, crystalline	
15		II	Brown-grey, crystalline	Similar to 10, with areas of brown-green glass
16	1	I	Dense blue rock, fine-grained	Olivine basalt with dark base and secondary carbonates

(3) The lower rocks of both bores, particularly at Alfredton, contain much CO_2 and H_2O due to the formation of secondary carbonates as a result of long saturation with ground water. The chief effect of this in the analyses is to give a low percentage of SiO_2.

However, if we calculate without the CO_2 and H_2O, the percentage of SiO_2 in all the basalts of the Alfredton bore is approximately 50, while in the Ballarat Common series it would range from 48 to 52. Thus the original SiO_2 content varied very little from flow to flow.

The exact composition of the secondary carbonates and their effect on the percentages of CaO, MgO and FeO are not known, but it is quite clear that they are not entirely $CaCO_3$. Their effect has been neglected in calculating the mineral percentage, and the result of this is to give somewhat high values for olivine and the pyroxenes.

Many of the analyses, especially those of the Ballarat Common bore (Table 5), and all specimens of the top rock (Table 7), show high Fe_2O_3, some of which is contained in the iddingsite. Occasionally this gives rise to normative hematite and iron-free pyroxenes and olivine which are not actually present. In view of this and the general occurrence of both iddingsite and magnetite in these rocks, a more modative norm would be obtained by calculating one half of the Fe_2O_3 as magnetite, and the other half has hematite. Such a procedure would have the effect of increasing the amount of femic minerals and reducing the amount of normative quartz which is found in some cases. However, this suggested departure from the standard calculation has not been adopted.

TABLE 5

Chemical Analyses of Four Flows from Ballarat Common D.D. Bore No. 3

No. of core specimen	14	11	10	5	1
No. of flow	1	2	2	3	4
No. of analysis	I	II	III	IV	V
SiO_2	48.85	50.43	46.48	47.68	47.49
Al_2O_3	15.82	16.88	15.31	14.31	14.92
Fe_2O_3	.22	4.16	4.99	6.34	4.76
FeO	8.97	5.58	5.54	4.49	5.28
MgO	7.21	4.18	8.40	8.31	8.18
CaO	8.78	9.32	7.47	7.89	8.53
Na_2O	2.72	3.32	2.46	2.98	2.76
K_2O	.78	.94	.80	.94	1.02
TiO_2	2.11	1.34	1.86	2.26	2.34
P_2O_5	.28	.27	.24	.14	.21
H_2O+	1.53	1.37	2.67	1.95	2.86
H_2O-	.30	.36	3.43	2.35	2.00
CO_2	2.21	2.23	.61	Nil	Nil
Total	99.78	100.38	100.26	99.64	100.35
Composition of plagioclase	Ab 46	Ab 51	Ab 45	Ab 54	Ab 50
Q	—	3.48	1.31	1.14	.07
Or	4.62	5.56	4.73	5.56	6.03
Ab	23.06	28.07	20.96	25.15	23.32
An	28.58	28.36	28.21	22.88	25.27
Di	10.81	13.02	5.75	11.97	12.36
Hy	18.83	8.75	21.27	15.23	16.58
Ol	4.88	—	—	—	—
Mag	.34	6.03	7.24	7.91	6.91
Hem	—	—	—	.88	—
Il	3.95	2.56	3.54	4.30	4.45
Ap	.61	.59	.53	.31	.46
Total	95.68	96.42	93.54	95.33	95.45

Flows 1, 2, 3, 4: Iddingsite labradorite basalts.

Analyst: H. Yates

Variation in the Top (4th) Basalt

This basalt forms the surface rock of practically the whole of Ballarat West and Sebastopol, an area of 25 square miles. It failed to cover the Ordovician bedrock north-east of Lake Wendouree, and also near the intersection of Sturt and Raglan Streets where a small steptoe was formed. The coarse-grained doleritic texture is remarkably constant in the surface part of the sheet and the colour is generally light grey, although it is darker than usual in the cores of the D.D.

TABLE 6

Chemical Analyses of Four Flows from Alfredton D.D. Bore No. 4

No. of core specimen	16	15	12	10	8	4	3	2
No. of flow ..	1	2	2	2	3	3	3	4
No. of analysis ..	I	II	III	IV	V	VI	VII	VIII
SiO_2	46.52	46.22	44.95	45.54	49.92	50.22	50.15	48.31
Al_2O_3	14.40	14.57	15.42	13.49	15.51	15.77	15.06	15.30
Fe_2O_3	1.94	1.94	1.55	2.98	1.62	1.80	1.93	4.51
FeO	7.79	7.72	9.50	7.97	8.58	8.05	8.58	5.68
MgO	5.74	5.51	5.39	6.89	8.47	7.95	8.40	8.65
CaO	9.90	8.68	8.10	8.84	8.40	8.56	8.53	7.95
Na_2O	2.82	3.10	2.86	2.68	3.06	3.18	3.20	3.14
K_2O	.90	.80	.91	.76	.64	.78	.74	.64
TiO_2	2.22	2.14	2.18	1.73	2.25	2.32	1.92	2.17
P_2O_5	.24	.31	.31	.24	.30	.32	.27	.30
H_2O+	4.07	4.71	4.65	3.51	.85	1.11	.58	1.87
H_2O-	.26	.26	.35	1.60	.16	Nil	.32	1.80
CO_2	3.41	3.85	4.07	3.65	Nil	Nil	Nil	Nil
Total ..	100.21	99.81	100.24	99.88	99.76	100.06	99.68	100.32
Composition of plagioclase ..	Ab 54	Ab 54	Ab 49	Ab 51	Ab 51	Ab 52	Ab 54	Ab 59
Or	5.34	4.74	5.40	4.51	3.89	4.62	4.45	3.88
Ab	23.85	26.20	24.18	22.65	26.18	26.99	27.04	26.57
An	23.94	23.45	26.51	22.50	26.41	26.13	24.47	25.66
Di	19.24	14.37	9.64	16.09	10.79	11.68	13.06	9.36
Hy	8.63	11.60	10.30	13.28	17.75	15.99	14.51	18.65
Ol	3.90	3.06	8.07	3.96	6.47	5.78	8.07	1.21
Mag	2.82	2.82	2.25	4.32	2.34	2.61	2.78	6.53
Il	4.22	4.07	4.14	3.29	4.26	4.39	3.65	4.12
Ap	.53	.68	.68	.53	.65	.69	.59	.66
Total ..	92.47	90.99	91.17	91.13	98.74	98.89	98.62	96.64

Flows 1, 2, 3: Olivine labradorite basalts.
Flow 4: Olivine andesine basalt.

Analyst: H. Yates.

bores. The term "oatmeal rock" has been heard in reference to this basalt and is especially applicable west of Lake Wendouree where the plagioclase has tabular habit. In places augite occurs in two generations, but in other parts as fine grains only. Olivine and the iron ores are not abundant and the olivine is much iddingsitized. Slides 1542 and 1405 of the Mines Department collection show interesting textural and mineralogical variations of this rock in the form of thin layers in the main flow exposed in the Alfredton quarry. No. 1542 is relatively very coarse-grained, the augite and plagioclase crystals and also thin ilmenite rods being up to 5 m.m. in length. Zircon needles are numerous. Slide 1405 is finer grained, but has a great concentration of zircon needles and ilmenite. Olivine is rare in both these slides.

The top rock has a maximum thickness of 160 ft. in the vicinity of Lake Wendouree, and so should be most suitable for detailed study in search of variation of composition and texture at different depths. However, no specimens are available from the mine shafts, and the Alfredton bore specimens were too few to give much information in this direction, although specimen No. 2 is darker and finer grained than the top of the flow, and also has lower percentages of SiO_2 and CaO but higher MgO (cf. Analyses I, II, Table 7). Chemical analyses of the surface part of the "top rock" at several points are given in Table 7. With the exception of No. III the rocks are basic andesine- to labradorite-basalts, the composition of the plagioclase ranging form Ab_{56} to Ab_{44}. Analysis No. III is of the coarse-grained acid andesine basalt "layer" (Ab_{62}) collected by Mr. Baragwanath from the Alfredton quarry, and referred to by Edwards (1938, p. 270) as oligoclase basalt. The series of analyses shows no marked variation in the composition of the top rock in horizontal extent.

Lateral Variation of the Third Flow

Like the top flow, this earlier flow had spread over almost the whole of the Ballarat West area. In the city area proper it extended further eastwards than

TABLE 7

	I	II	III	IV	V	VI	VII	VIII
SiO_2	48.31	50.03	50.17	49.27	50.45	49.56	47.49	50.33
Al_2O_3	15.30	15.54	14.43	15.33	14.96	16.30	14.92	17.43
Fe_2O_3	4.51	5.80	8.02	8.40	6.26	3.51	4.76	5.48
FeO	5.68	5.40	3.65	4.71	4.72	6.48	5.28	3.73
MgO	8.65	6.64	7.66	3.47	6.98	7.86	8.18	6.17
CaO	7.95	9.02	8.96	7.05	8.60	9.04	8.53	8.28
Na_2O	3.14	3.44	3.04	3.54	2.93	3.42	2.76	2.88
K_2O	.64	.92	1.08	2.25	1.08	.68	1.02	.60
TiO_2	2.17	2.59	1.70	3.71	1.93	2.26	2.34	2.04
P_2O_5	.30	.33	.33	.61	.37	.35	.21	.30
H_2O+	1.87	.47	.68	.48	.79	.73	2.86	2.16
H_2O-	1.80	.51	.85	.54	.97	.28	2.00	.18
CO_2	—	—	Nil	Nil	Nil	—	—	—
Others	—	—	.28	.46	.34	—	—	—
Total ..	100.32	100.69	100.85	99.82	100.38	100.47	100.35	99.58
Plagioclase ..	Ab 59	Ab 56	Ab 55	Ab 62	Ab 52	Ab 53	Ab 50	Ab 44
Q	—	.69	2.92	4.04	4.72	—	.07	6.52
Or	3.88	5.42	6.40	13.34	6.40	4.03	6.03	3.56
Ab	26.57	29.08	25.69	29.92	24.78	28.91	23.32	24.34
An	25.66	24.21	22.51	19.25	24.44	27.13	25.27	32.82
Di	9.36	14.56	15.41	9.16	12.33	12.31	12.36	4.92
Hy	18.65	12.93	12.02	4.44	12.04	11.57	16.58	13.15
Ol	1.21	—	—	—	—	5.36	—	—
Mag	6.53	4.24	6.83	4.42	9.08	5.09	6.91	6.14
Hem	—	2.88	3.31	5.36	—	—	—	1.25
Il	4.12	4.92	3.23	7.05	3.67	4.29	4.45	3.88
Ap	.66	.72	.72	1.34	.81	.77	.46	.66
Total ..	96.64	99.65	98.04	98.32	98.27	99.46	95.45	97.24

I. 4th flow; Specimen No. 2, Alfredton D.D. bore; Analysis VIII from Table 6.
II. 4th flow; from the surface at Alfredton South near the Cattle Yards. *Analyst:* A. J. Hall.
III. 4th flow; from near the surface at the City Quarry, Alfredton. *Analyst:* A. G. Webb.
IV. 4th flow; acid-andesine layer, from the City Quarry, Alfredton. *Analyst:* A. J. Hall.
V. 4th flow; from west bank of Yarrowee Creek Ballarat South, near old pyrites works.
VI. 4th flow; olivine iddingsite andesine basalt, from the surface at Bonshaw Creek, Ballarat South.
VII. 4th flow; Specimen No. 1, Ballarat Common, D.D. bore; Analysis V, Table 5.
VIII. Ophitic olivine iddingsite labradorite basalt; from the surface at Napoleon, 8 miles south of Ballarat.

the top rock, but is now covered by thick clays east of Yarrowee Creek. It outcrops only at a few places in Ballarat South, forming low hills on the east side of the creek, and also narrow exposures along the base of the cliff where the creek has cut through the top rock. The third rock has fairly constant lithological character, being fine-grained and dense. Its colour is brownish-grey at Yarrowee Creek and light bluish-grey in the Alfredton bore (five specimens). Most samples examined of this flow are ophitic olivine andesine basalt with plagioclase, Ab_{55} to Ab_{49}. The ophitic fabric is exceptionally well developed in the Yarrowee Creek specimen. Study of the chemical analyses (Table 8) reveals considerable variation of certain important oxides in the upper part of the third rock at different places. This shows that the conditions of solidification were not uniform throughout the whole of the sheet. Thus, low MgO and Fe_2O_3 in the eastern portion of the flow indicates sinking of early formed crystals of olivine, augite and magnetite here. However, in view of the fact that several analyses of the same flow at different depths in the Alfredton bore show no marked variation of MgO it is suggested that the sinking of crystals in this case did not take place entirely *in situ*, but to a great extent progressively as the flow proceeded eastwards, so that the eastern edge of this basalt is impoverished in olivine and magnetite, although ilmenite is abundant, as shown by the exceptionally high TiO_2 content. The author's analysis of the third rock at Yarrowee Creek does not agree very closely with that made by Hall. The latter's sample was from a little further south, and the high value obtained for CO_2 suggests that it was not as fresh as possible.

Vertical Variation of the Third Flow

Three specimens of this rock from different depths in the Alfredton D.D. bore have been analysed (Nos. V, VI, VII, Table 6) and very uniform composition of the sheet is indicated. The only noticeable variation is a slight impoverishment of the upper level in ilmenite and apatite due to sinking of these minerals.

Variation of the Second Flow

Three specimens of this rock from the Alfredton bore were chosen for analysis, so that the depth intervals would be considerable (Nos. II, III, IV, Table 6). However, only minor variations of composition are noted.

The low MgO content suggests that olivine crystallized to some extent in the magma reservoir and sank before extrusion of this flow. Then, after extrusion, the lava cooled slowly, allowing the olivine constituents to become concentrated in the upper levels without forming large crystals and sinking to any considerable extent. The lower TiO_2 and P_2O_5 in the upper part of the sheet is explained by sinking of ilmenite and apatite crystals after extrusion.

A core specimen from the Cardigan D.D. bore, taken at a depth of 200 ft., corresponds in level with the second flow at Ballarat West. It is a blue vesicular olivine andesine basalt (Ab_{55}) with abundant dark glassy base. However, chemically it does not resemble either the second or first flow at Ballarat West, having a very high MgO content (Analysis V, Table 8).

2. Basalts of the Warrenheip, Gong Gong and Creswick Areas

Four miles due east of the eastern edge of the Ballarat West basalts we come to the meridional western edge of the Warrenheip basaltic plateau whose average surface altitude is 400 ft. higher than Ballarat West. The first basalt poured out

TABLE 8

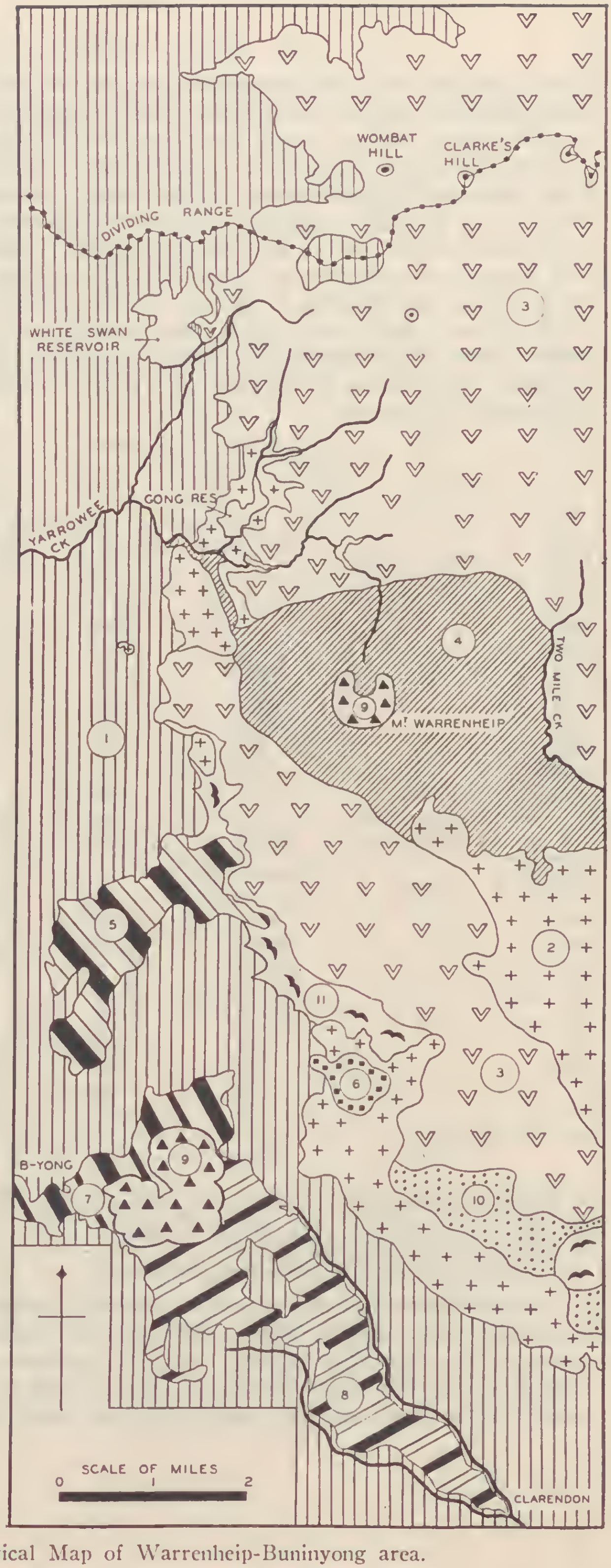
	I	II	III	IV	V
SiO_2	50.15	47.68	51.69	46.81	49.95
AL_2O_3	15.06	14.31	15.17	12.94	14.53
Fe_2O_3	1.93	6.34	.35	1.62	2.75
FeO	8.58	4.49	7.64	8.39	8.18
MgO	8.40	8.31	4.59	6.81	8.92
CaO	8.53	7.89	8.19	9.51	8.98
Na_2O	3.20	2.98	2.80	2.76	3.16
K_2O	.74	.94	1.00	.88	.94
TiO_2	1.92	2.26	2.93	1.60	2.49
P_2O_5	.27	.14	.27	.25	.33
H_2O+	.58	1.95	1.24	.90	.10
H_2O-	.32	2.35	1.17	.50	—
CO_2	—	—	2.54	6.85	—
Others	—	—	—	.14	—
Total ..	99.68	99.64	99.58	99.96	100.33
Plagioclase	Ab 54	Ab 54	Ab 49	—	Ab 55.6

I. Upper part of 3rd flow; Specimen No. 3, Alfredton D.D. bore; Analysis VII from Table 6.
II. Upper part of 3rd flow; Specimen No. 5, Ballarat Common D.D. bore; Analysis IV from Table 5.
III. 3rd flow, from Yarrowee Creek at Prest Street, Ballarat South. It is ophitic labradorite basalt. *Analyst:* H. Yates.
IV. 3rd flow, from Yarrowee Creek at Prest Street, Ballarat South. It is ophitic labradorite basalt. *Analyst:* A. J. Hall.
V. Olivine andesine basalt from 200 feet depth in the D.D. bore at Cardigan, west of Ballarat. *Analyst:* H. Yates.

in this area was the very extensive Clarke's Hill sheet which flowed away in all directions, but principally southwards, from the prominent vent 1¼ miles south of Dean. The lava flowed over an irregular granitic surface, as shown by evidence from D.D. bores at Warrenheip and three miles south of Clarke's Hill.

The adamellite outcrops near Warrenheip railway station, at Woodman's Hill and at Gong Gong Reservoirs, and in the vicinity of these outcrops the basalt is naturally thin—about 30 ft. at Gong Gong. However, thicknesses up to 200 ft. were found in the D.D. bores. The Clarke's Hill flow is still the surface rock of the greater part of the Parish of Bungaree and Dean, and of a considerable area west of Lal Lal Creek, extending from Warrenheip to Lal Lal (Fig. 2). Within a restricted area surrounding Mt. Warrenheip the Clarke's Hill flow is overlain by a second, less extensive basalt. This lava was not poured out from Mt. Warrenheip except for a small amount which flowed due north out of the breached crater in the final stage of the vulcanicity and formed a very gentle uniform surface slope. Most of it issued from subsidiary vents just west and east of the mountain and marked by low hills. From the western vents the lava flowed south, west and north-west and solidified with a steep edge trending west by north between the mountain and the railway station, then swinging northwards towards Gong Gong. To the north-west of the vent this lava crossed the western edge of the Clarke's Hill basalt and turned west down the ancestor of the present Yarrowee Creek, forming a narrow tongue half a mile long. From the subsidiary vents east of Mt. Warrenheip the lava flowed north, south and east. Its boundary has determined the course of the Two Mile Creek, west of Bungaree.

The Clarke's Hill basalt is a bluish-grey rock in which very numerous phenocrysts of olivine up to 5 mm. in length can be seen in hand specimens. There are also occasional phenocrysts of augite and glassy andesine. Its chief microscopical features are that the base is holocrystalline, and some of the olivine and augite is



1. Ordovician.
2. Granite.
3. Clarke's Hill basalt.
4. Warrenheip basalt.
5. Green Hill basalt.
6. Yendon basalt.
7. Buninyong basalt.
8. Buninyong-Clarendon basalt.
9. Mt. Warrenheip and Mt. Buninyong, scoria cones.
10. Kaolinized granite.
11. Recent alluvium.

Fig. 2.—Geological Map of Warrenheip-Buninyong area.

glomeroporphyritic. The younger Warrenheip basalt is extremely fine-grained but holocrystalline, and it too contains a few large phenocrysts of glassy andesine. The plagioclase laths are well developed, though small, the augite is in tiny grains and the olivine occurs as micro-phenocrysts of average grainsize 0·2 mm. This rock, both at Warrenheip and Gong Gong, contains corroded grains of quartz, which were probably caught up by the magma as it was ascending through decomposed adamellite. The chemical analyses (Table 9) show that the norms of both basalts contain olivine, nepheline and andesine, and both are much more alkaline than the Ballarat West series. They are closely related to the basalts of the Bullarook-Newlyn area to the north (Analysis No. V). The author's analysis of the Clarke's Hill flow does not agree with Clarke's analysis (No. II, Table 9) in which the very low percentage of MgO is incompatible with the actual mineral composition of the rock.

TABLE 9

	I	II	III	IV	V
SiO_2	50.06	48.56	46.33	48.10	47.46
Al_2O_3	14.73	19.36	17.78	17.14	16.12
Fe_2O_3	1.61	1.10	2.25	4.02	2.96
FeO	8.49	9.21	6.97	6.42	9.39
MnO	—	.09	—	—	.25
MgO	7.94	5.21	7.00	6.32	5.70
CaO	8.27	8.52	7.76	7.91	7.27
Na_2O	4.06	2.62	4.04	4.28	3.51
K_2O	1.59	1.57	2.40	2.14	1.74
TiO_2	2.62	2.13	2.85	2.71	3.10
P_2O_5	.44	.50	.71	.58	.78
H_2O+	.47	1.07	1.25	.57	.57
H_2O-	.11	.20	.34	.14	.72
Total ..	100.39	100.22	99.68	100.33	99.57
Plagioclase	Ab 65	—	Ab 48	Ab 57	Ab 58
Or	9.40	9.32	14.19	12.66	10.33
Ab	29.47	22.25	19.81	26.59	29.66
An	17.23	36.37	23.24	21.19	23.04
Ne	2.62	—	7.76	5.19	—
Di	17.32	2.56	8.77	11.49	6.61
Hy	—	14.02	—	—	5.10
Ol	15.47	7.62	14.04	10.25	11.36
Mag	2.32	1.67	3.26	5.83	4.29
Il	4.98	4.04	5.42	5.15	5.89
Ap	.96	1.09	1.55	1.27	1.71
Total ..	99.84	—	98.04	99.62	97.99

I. Porphyritic olivine andesine basalt, Clarke's Hill flow from Gong Gong Quarry. *Analyst:* H. Yates.
II. Idem. *Analyst:* J. Clark.
III. Olivine labradorite basalt, 1 mile N.W. of Mt. Warrenheip. *Analyst:* H. Yates.
IV. Idem. From Yarrowee Creek, Gong Gong. *Analyst:* H. Yates.
V. Olivine Andesine basalt from Newlyn, parish of Spring Hill. *Ann. Rep. Sec. Mines, Vic.*, 1911, *page* 62.

Other alkaline basalts occur at several prominent points of eruption in the Creswick area, namely Spring Mount, Mt. Hollowback, Mt. Pisgah and Mt. Rowan. They are porphyritic types, the phenocrysts being augite, olivine and andesine. Their analyses (Table 10) gave high Al_2O_3 and alkalis, but low MgO and SiO_2, so that nepheline appears in the norm of two of them. Augite phenocrysts are best developed in the Newlyn, Spring Mount and Mt. Rowan basalts, while andesine phenocrysts are very prominent in the Egan's Town, Spring Mount and Mt. Hollowback rocks.

The Mt. Pisgah basalt has small phenocrysts of olivine, augite and andesine, and contains occasional gabbroic xenoliths. The basalt at Mt. Blowhard has a coarse ophitic texture and is less alkaline than the others.

TABLE 10

	I	II	III	IV	V	VI
SiO_2	46.82	46.36	46.91	60.16	47.66	49.98
Al_2O_3	19.26	19.87	17.73	24.90	17.30	16.18
Fe_2O_3	1.79	.87	5.14	—	1.72	3.73
FeO	7.37	8.96	6.47	—	8.37	6.23
MgO	5.65	5.45	4.94	.04	7.82	7.70
CaO	7.94	7.34	6.96	7.26	8.20	8.84
Na_2O	3.68	4.02	3.60	7.24	3.52	3.08
K_2O	1.92	1.64	1.98	.94	1.24	1.12
TiO_2	2.74	2.43	2.97	—	3.20	2.12
P_2O_5	.76	.47	.53	—	nd .50	nd .50
H_2O+	1.43	1.15	1.64	—	.42	.45
H_2O-	.31	1.33	.96	—	.67	.52
Total ..	99.67	99.89	99.83	100.54	100.62	100.45
Comp. of plagioclase	Ab 48	Ab 46	Ab 55	Composition Or 5 Ab 62 An33	Ab 52	Ab 51
Or	11.36	9.70	11.72	—	7.34	6.63
Ab	26.13	24.84	30.43	—	28.78	26.19
An	30.31	31.27	26.32	—	27.92	26.89
Ne	2.69	4.97	—	—	.52	—
Di	3.41	1.72	3.79	—	7.78	10.93
Hy	—	—	4.18	—	—	16.69
Ol	14.51	17.96	6.53	—	17.53	1.60
Mag.	2.60	1.28	7.45	—	2.50	5.41
Il	5.21	4.62	5.64	—	6.08	4.03
Ap	1.70	1.03	1.17	—	1.09	1.09
Total ..	97.92	97.39	97.23	—	99.54	99.46

I. Porphyritic olivine labradorite basalt, parish of Spring Hill.
II. Porphyritic olivine labradorite basalt, Mt. Hollowback.
III. Porphyritic andesine basalt, Mt. Rowan.
IV. Potash-andesine phenocrysts in Mt. Hollowback basalt.
V. Olivine andesine basalt, Mt. Pisgah.
VI. Ophitic iddingsite labradorite basalt, Mt. Blowhard.

Analyst: H. Yates.

3. MOUNT WARRENHEIP

Mt. Warrenheip is a breached fragmental cone which accumulated on top of the Clarke's Hill basalt. It was briefly described and also figured in hachure by Gregory (1903). The summit of the mount is 2,430 ft. above sea-level, and its base is 100 ft. higher on the west and north sides than on the south and east, due to the presence of subsidiary cones along the northern and western margins. The height of the cone itself varies from 450 ft. to 550 ft. and the surface in the crater is 300 ft. below the rim. The surface gradient on the south and east slopes is approximately 30°. The cone was probably built up rapidly during a violent explosive phase which initiated the vulcanicity at this vent, and the volcano remained active until the final effusion of a small lava stream to the north, simultaneously with the pouring out of more extensive lava from the subsidiary vents to the west. Just prior to this, however, the northern rim of the crater was breached by another violent explosion.

The fragmental materials composing the mountain include vesicular basalt, scoria, volcanic bombs, blocks of adamellite, and reef quartz. The adamellite and quartz are portions of the pre-basaltic surface rocks which were burst through by the explosions. The volcanic bombs vary in size from 1 in. in diameter to 2 ft. 6 in. in length, and there is also some variation of shape. The large majority are ellipsoidal and have protuberances at both ends of the major axis, the axis of rotation. A few small biconvex buttons with complete flanges were found, while one specimen is a biconvex disc with a tail. Many of the bombs have a kernel of olivine, often comparatively large and giving the specimen an appreciably higher specific gravity. In a few cases there is a core of decomposed adamellite, while some bombs have no kernel. The olivine kernels are cognate xenoliths but the adamellite kernels are 'strangers'. Concentric flow lines are nearly always present, indicating solidification during rotation in the air. The vesicular basalt, scoria and volcanic bombs contain sporadic granular masses of olivine, also crystals and grains of titanaugite and anorthoclase (analyses, Table 11). All three minerals were

TABLE 11

	I	II	III	IV	V
SiO_2	65.64	61.93	48.89	49.00	43.16
Al_2O_3	20.52	22.08	9.41	8.66	—
Fe_2O_3	Nil	tr.	1.78	2.78	—
FeO	Nil	—	5.83	6.52	14.14
MgO	Nil	tr.	14.38	14.53	43.08
CaO	Nil	Nil	16.80	15.64	—
Na_2O	10.36	8.84	1.14	1.12	—
K_2O	2.25	6.34	Nil	0.05	—
TiO_2	—	—	1.65	1.27	—
P_2O_5	—	—	—	Nil	—
H_2O-	—	—	0.30	0.06	—
H_2O-	—	—	—	0.14	—
Others	—	—	—	0.44	—
Total ..	98.77	99.19	100.18	100.21	100.38

I. Anorthoclase, Mt. Warrenheip. *Analyst:* H. Yates.
II. Glassy tabular felspar crystals from dense basalt, Magorra, near Jumbunna. *Analyst: Geol. Surv. Vic.*, 1901.
III. Titanaugite, Mt. Warrenheip. *Analyst:* H. Yates.
IV. Augite, Mt. Noorat, near Terang. *Analyst:* A. J. Hall.
V. Olivine, Mt. Warrenheip. *Analyst:* H. Yates.

undoubtedly early crystallization products of the olivine-basalt magma, and the pure lime-free anorthoclase suggests considerable cupola differentiation at this point. The mineral occurs only in small quantities, but sufficient was found for analysis and sectioning. It is quite colourless and the section shows the characteristic "cross hatch" twinning lamellae. The refractive index is lower than that of canada balsam and the optical character is negative.

The only other occurrence of lime-free felspar in Victorian basalts or associated scoria, etc., to which reference has been found is that from dense basalt at Magorra near Jumbunna (Mahoney, 1928). The augite at Wt. Warrenheip agrees fairly closely in composition with that from Mt. Noorat.

4. Basalts of the Buninyong-Mt. Mercer Area

In the Buninyong-Mt. Mercer area there were several points of volcanic eruption, chief of which from north to south are Green Hill, Mt. Buninyong, Grenville Hill, Hardie's Hill, Mt. Mercer and Mt. Lawaluk, with Cargerie Hill to the east. This series of vents is separated from Mt. Warrenheip by a five-mile belt containing no points of eruption. The small flow from Green Hill moved north-east to meet the edge of the Clarke's Hill flow at Navigator. Mt. Buninyong, two miles south-east of Green Hill, rises to the same altitude as Mt. Warrenheip. It is more composite in structure than Warrenheip, however, comprising several points of effusion in addition to the main cone which was built up of ejected fragments chiefly, including volcanic bombs. It is clear that at least two lava streams flowed from the Mt. Buninyong vent. The earliest was the Clarendon flow, which moved south and south-east. After this the main fragmental cone was formed and later breached by explosions on the north-west rim. Finally an extensive narrow lava stream flowed out of this breach, westwards at first for two miles, then south-west down a tributary valley of the Durham Lead. The small flow from Grenville Hill moved north to meet this Buninyong basalt. The basalts of the Durham Lead, between Buninyong and Mt. Mercer, were referred to at some length by Etheridge and Murray (1874) when the auriferous lead was being mined. With the aid of data from the Pioneer, Duke of Cornwall, City of Manchester and other shafts they showed that the deep narrow lead was filled by two separate lava streams for the full length of ten miles from Durham Lead to

Table 12

	Megascopical features	Microscopical features
I. Green Hill Basalt . .	Blue-grey, fine grained crystalline, occasional phenocrysts of olivine augite and plagioclase	Very fine-grained, holocrystalline, with occasional phenocrysts of olivine, to 1 m.m.
II. Yendon Basalt . .	Dense fine-grained blue rock with a few phenocrysts of plagioclase and olivine	—
III. Buninyong Basalt .	Dense, bluish-grey, fine grained	Olivine iddingsite basalt, good fluidal fabric
IV. Clarendon Basalt . .	Blue, fine-grained	Fine grained, holocrystalline. Microphenocrysts of olivine.
V. Grenville Hill Basalt	Blue, fine grained, crystalline with occasional phenocrysts of olivine and augite	Porphyritic augite olivine basalt, good trachytic fabric
VI. Garibaldi Basalt . .	Blue, coarse grained	Ophitic olivine iddingsite basalt
VII. Hardie's Hill Basalt	Similar to No. V	Similar to No. V
VIII. Mt. Mercer Basalt .	Blue-grey, fine grained	Fine grained, pilotaxitic basalt with microphenocrysts of olivine
IX. Mt. Lawaluk Basalt	Dark Blue, fine grained	Black glass abundant. Plagioclase laths and microphenocrysts of olivine and augite

Mt. Mercer. The first flow was 88 ft. thick and the second 113 ft. in the Duke of Cornwall shaft near Hardie's Hill.

These lavas certainly flowed southwards, and probably issued from the Napoleon and Cambrian Hill vents because the upper flow at Garibaldi, ophitic olivine iddingsite basalt, closely resembles the surface rock at Napoleon, but is quite unlike the flows from Mt. Buninyong and Grenville Hill. Coulson (1937) described the Durham Lead basalt as containing abundant oligoclase, but the actual flow referred to was not stated. At the present time no specimens of the lower sheet are available for study.

The Durham Lead basalts are locally covered by the thin flow from Hardie's Hill, but this was very limited in extent. In the vicinity of the vent it was finally concealed by beds of ash and volcanic breccia, which form a well defined rim around the large crater. Further south the narrow Durham Lead basalts pass beneath the extensive Mt. Mercer flow, which moved southwards chiefly. To the east of the Mt. Mercer flow another broad basalt sheet moved south-west from the Green Hill or Collier's Hill in the Parish of Cargerie, and the junction of these

TABLE 13

	I	II	III	IV		V	VII
SiO_2 ..	47.31	46.72	50.01	50.21	49.10	47.81	50.28
Al_2O_3 ..	16.15	18.80	16.86	17.28	16.71	15.40	17.57
Fe_2O_3 ..	5.28	1.53	5.51	3.04	3.18	6.37	4.31
FeO ..	6.53	7.29	4.96	5.98	6.80	5.61	4.96
MgO ..	6.30	6.44	3.85	4.58	7.72	7.58	3.86
CaO ..	7.84	7.72	7.38	7.52	7.90	8.48	6.98
Na_2O ..	3.54	4.56	3.42	3.80	3.55	3.94	4.08
K_2O ..	1.66	2.42	1.84	1.78	.96	1.04	1.66
TiO_2 ..	3.00	2.85	3.71	3.42	1.87	2.42	3.71
P_2O_5 ..	.43	.74	.35	.45	.29	.44	nd.35
H_2O+ ..	.96	.80	1.14	.89	.89	.91	.65
H_2O- ..	1.10	.24	.76	.88	.62	.39	1.37
Total ..	100.10	100.11	99.79	99.83	99.59	100.39	99.78
Plagioclase .	Ab 58	Ab 46	Ab 55	Ab 58	Ab 54	Ab 60	Ab 60
Q	—	—	4.48	.34	—	—	2.14
Or	9.82	14.33	10.88	10.57	5.68	6.16	9.81
Ab	29.90	19.01	28.91	32.12	30.00	33.30	34.48
An	23.21	23.63	25.17	24.77	26.78	21.23	24.69
Ne	—	10.60	—	—	—	—	—
Di	10.22	8.02	7.13	7.67	8.44	14.06	5.97
Hy	2.97	—	6.33	10.67	8.96	.15	6.89
Ol	7.56	14.21	—	—	9.39	9.36	—
Mag ..	7.66	2.22	5.23	4.41	4.62	9.23	5.23
Hem ..	—	—	1.91	—	—	—	.71
Il	5.70	5.42	7.05	6.52	3.55	4.60	7.05
Ap	.93	1.62	.77	.98	.64	1.03	.76
Total ..	97.97	99.06	97.86	98.05	98.06	99.12	97.73

I. Olivine Andesine basalt, Green Hill. *Analyst:* H. Yates.
II. Olivine nepheline labradorite basalt, Clarendon. *Analyst:* H. Yates.
III. Andesine basalt, Buninyong. *Analyst:* H. Yates.
IV. Andesine basalt, Grenville Hill. *Analyst:* H. Yates.
V. Olivine andesine basalt, Hardie's Hill. *Analyst:* H. Yates.
VI. Olivine andesine basalt, Mt. Mercer. *Analyst:* H. Yates.
VII. Andesine basalt, Yendon. *Analyst:* H. Yates.

FIG. 3.—Geological Map of the Gordon-Lal Lal area.

1. Ordovician.
2. Granite.
3. Clarke's Hill basalt.
4. Warrenheip basalt.
5. Wallace to Lal Lal basalt.
6. Iron ore deposit.
7. Post-Pliocene sands, etc.
8. Recent alluvium.

two lava fields has determined the channel of the present Leigh River which no longer follows the general course of the Durham Lead as it does further north.

The principal megascopical and microscopical characters of the basalts in the Buninyong-Mt. Mercer area are given in Table 12.

Newberry made chemical analyses of some of the basalts from the Durham Lead. They were incorporated in the Report by Etheridge and Murray, but they are unsuitable in form for comparison with the present writer's analyses (Table 13).

Study of the table shows that the basalts from the vents in the northern part of the area—Green Hill, Buninyong, Yendon and Grenville Hill—are very alkaline types, chemically related to the Warrenheip series further north. Nepheline appears in the norm of the Clarendon flow, although this mineral was not detected in the slides. Another common feature of this group (Analyses I-IV) is low MgO content, and consequently a low total amount of pyroxenes and olivine. The rocks from Hardie's Hill and Mt. Mercer are less alkaline than the Buninyong group, but much more alkaline than the Ballarat West series.

5. Basalts at Lal Lal Falls

In addition to the Clarke's Hill flow which approached Lal Lal from the north-west down the valley of the ancestor of the present Lal Lal Creek, two thick basalt streams reached the ancient Lal Lal basin from the north. These are exposed in section in the south cliff at Lal Lal falls. The present surface of the top flow near Lal Lal is practically horizontal, but the gentle southerly slope further north shows that the lava probably issued from a vent at Springbank, about two miles north of the township of Wallace, and flowed generally southwards down the valley of the ancestor of the Western Moorabool River, that is, parallel to the adjacent Clarke's Hill flow (Figs. 3, 4, 5).

Near Lal Lal Falls the upper basalt has a maximum thickness of 50 ft. while the lower one shows a face 70 ft. thick. This, however, is not the maximum thickness of the first flow because the gutter of the deep lead filled by this basalt is probably at least 1,000 ft. north-west of the falls and probably at least 50 ft. lower than the bottom of the falls. Thus the total thickness of the two basalt sheets is approximately 170 ft.

Both rocks have very good vertical columnar jointing but the average width of the columns in the top rock, 3 ft., is only half that in the bottom rock, due to slower cooling of the latter. The junction between the two sheets is well defined in the cliff section and presents the following features:

(1) softy clayey decomposed upper portion of the bottom rock;
(2) solid but slightly vesicular base of the top rock;
(3) change of width of columns;
(4) change of lithological character.

At the bottom of the waterfall the basalt rests on decomposed adamellite. A sample of this was examined by Mr. G. Baker, who found a few grains of the minerals tourmaline, zircon, rutile and andalusite, suggesting a possible sedimentary origin. However, it is more likely that the resistant minerals were eroded from the contact aureole above the granitic cupola and remained on its weathered surface.

Petrographical Descriptions

Macroscopically the bottom basalt has dark bluish-grey colour and is very fine-grained and dense. It is very uniform from top to bottom of the sheet. The

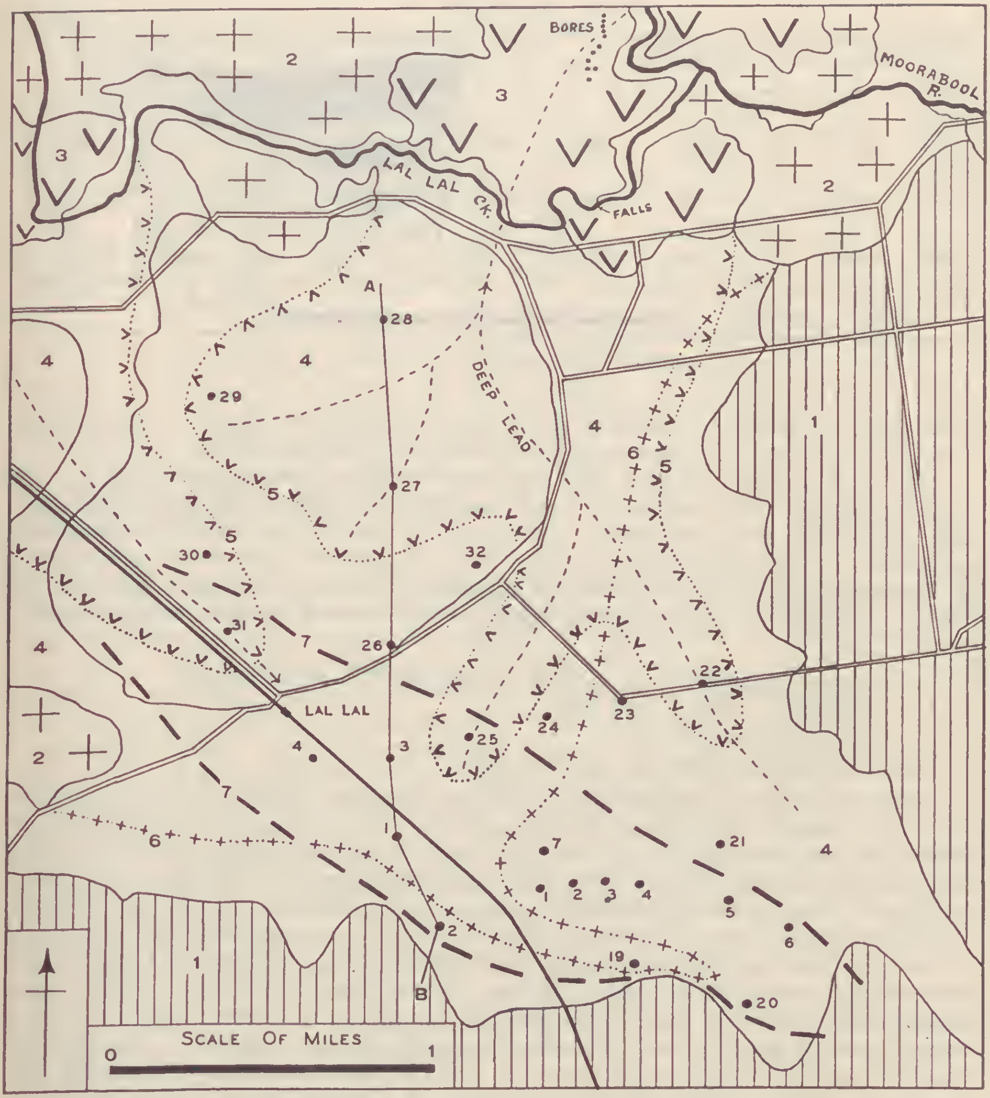


Fig. 4.—Geological Map of Lal Lal, showing bores (numbered dots).

Surface outcrops:
1. Ordovician.
2. Granite.
3. Basalt.
4. Post-Pliocene sands and alluvium.
5. Approx. sub-surface basalt boundaries.
6. Approx. sub-surface granite boundary.
7. Approx. boundary of sub-surface lignite fault basin.

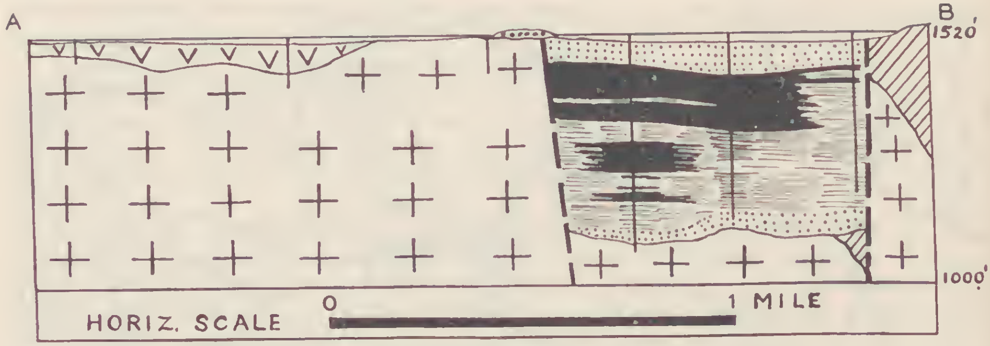


Fig. 5.—Section AB through the lignite basin at Lal Lal.

upper basalt is distinctly coarser grained and has light grey colour. It too is very dense and uniform. No phenocrysts are visible in hand specimens.

Microscopic examination of thin sections shows the bottom rock to be a very felspathic basalt. The plagioclase occurs mainly as irregular grains, but there are some porphyritic laths and prisms. The augite grains are fine and have indefinite boundaries. Fresh olivine is not present, but this mineral is probably represented by numerous small irregular areas of iddingsite. Iron ores are abundant, chiefly cubes of magnetite. The top rock is a good type of olivine basalt, its chief features being:

(1) numerous phenocrysts of fresh olivine $\frac{1}{2}$ to 2 mm. in length;
(2) plagioclase laths $\frac{1}{2}$ to 1 mm.
(3) granular augite;
(4) thin plates of ilmenite up to 1 mm.

Chemical analyses reveal a marked difference between the two basalts. Although both are andesine basalt, the plagioclase is more basic (Ab_{55}) in the bottom rock than in the upper one (Ab_{65}). The Al_2O_3 content is much higher in the first flow and the MgO lower. This is due to greater development of felspar and paucity of olivine. Another notable feature is the exceptionally high percentage of TiO_2 (3·65) in the first flow. The analysis of the top sheet compares quite closely with that of the Clarke's Hill flow, the chief differences being higher MgO and alkalis in the latter, resulting in a small amount of normative nepheline, which is not found in the Lal Lal rock. The sections of these two basalts also are very similar, but the Lal Lal rock has somewhat less olivine, which occurs as smaller phenocrysts. The similarity between the rocks of these two extensive sheets and also the proximity of the vents from which they issued suggest approximate contemporaneity of extrusion from two different points of the same magma cupola.

Differentiation

It cannot be established with certainty that the two basalt sheets at Lal Lal Falls issued from the same vent, but this is probable because the first flow, as shown above, is very thick (120 ft.) here near its extremity and, being confined to the north-south valley of the Moorabool deep lead, could easily have flowed a distance of ten miles from the supposed vent at Springbank. Also, the slightly decomposed nature of the top of this basalt and the absence of sediment between

TABLE 14

	I	II	III		I	II	III
SiO_2 ..	50.12	48.90	50.06	Or ..	9.12	5.56	9.40
Al_2O_3 ..	18.59	13.63	14.73	Ab ..	33.15	31.18	29.47
Fe_2O_3 ..	.77	2.42	1.61	An ..	28.53	17.82	17.23
FeO ..	7.92	8.78	8.49	Ne ..	—	—	2.62
MgO ..	4.06	6.82	7.94	Di ..	1.17	19.19	17.39
CaO ..	6.76	8.77	8.27	Hy ..	14.43	4.41	—
Na_2O ..	3.92	3.68	4.06	Ol ..	2.29	9.53	15.47
K_2O ..	1.54	.94	1.59	Mag ..	1.12	3.50	2.33
TiO_2 ..	3.65	2.62	2.62	Il ..	6.89	4.98	4.98
P_2O_5 ..	.56	.32	.44	Ap ..	1.23	.70	.96
H_2O+ ..	1.52	3.60	.47				
H_2O- ..	.90	.09	.11				
Total ..	100.31	100.57	100.39	Total ..	97.93	96.87	99.84
Plagioclase ..	Ab55	Ab65	Ab65				

I. Andesine basalt, lower flow at Lal Lal Falls.
II. Olivine andesine basalt, upper flow at Lal Lal Falls.
III. Olivine andesine basalt, Gong Gong (Clarke's Hill flow). Analysis I, Table 9.

Analyst: H. Yates.

the two sheets indicate but a short interval between the two extrusions. Assuming, therefore, that they came from the same magma cupola, it is interesting to compare the two rocks as regards mineral composition. The abundance of plagioclase and paucity of olivine in the first (lower) sheet as compared with the upper one points to extensive differentiation in the magma prior to the initial extrusion. Olivine phenocrysts crystallized near the top and then sank to the lower levels of the cupola, where partial resorption took place. This left the upper part of the magma enriched in plagiolclase and augite constituents. The high TiO_2 content of the lower sheet suggests that a second stage in the fractional crystallization prior to extrusion was the concentration of ilmenite molecules in the upper level of the magma. Thus the first extensive lava stream from this vent was impoverished in olivine but rich in plagioclase (basic andesine) and ilmenite constituents, and these latter minerals crystallized after extrusion. The second lava flow contained the abundant olivine phenocrysts from the lower level of the cupola and, furthermore, its plagioclase, of later crystallization, was more acid andesine.

Both flows at Lal Lal Falls have very uniform lithological character from top to bottom and, in view of the negligible variation found in analyses of the individual Ballarat West basalts, a series of analyses at different depths was not undertaken in this case.

6. Basalts and Tuffs at Burrumbeet

In the immediate vicinity of Lake Burrumbeet, 12-15 miles west of Ballarat, the surface basalt is not more than 20 ft. thick, its base being exposed just above the lake level on the north shore. Here, and also on the southern slope of Mt. Callender, bedded volcanic tuff, passing into coarse agglomerate in plaçes, underlies the basalt. On the northern slope of Mt. Callender the same tuff beds were not covered by the final lava flow and now form the surface rock over an area of one square mile, including a prominent low hill one mile east of Mt. Callender. This was a separate vent whose final activity was of the explosive type. The principal local vents from which the final lava flows issued were Weatherboard Hill, Saddleback Hill and Mt. Callender. Boring investigations by the Department of Mines in 1890 and 1900 established the course of the Ballarat West deep lead between Lakes Burrumbeet and Learmonth and running north-west to the Avoca lead. The bores east of Lake Burrumbeet proved a total thickness of 355 ft. of volcanic materials, while the bores drilled south of Lake Learmonth proved up to 216 ft. of basalts and basaltic clays. No fragmental beds of definite volcanic origin were recorded in these bores, but the thick red clay and "gravelly clay and drift" beneath the basalt at Learmonth may possibly be of pyroclastic origin.

It is clear, therefore, that there was much volcanic activity in this area before the formation of the tuff and agglomerate beds, a conclusion which was arrived at independently by the author as a result of study of the ejected blocks in the agglomerate. These ejected blocks include:

(1) Coarse-grained porphyritic pink biotite granite, traversed in places by veins of aplite and graphic pegmatite.
(2) Very coarse-grained pegmatitic type of granite, consisting of large orthoclase crystals and subordinate quartz and biotite.
(3) Very light grey, fine-grained two-mica granite with muscovite subordinate to biotite. This type is rare.
(4) Numerous friable decomposed volcanic bombs with ellipsoidal shape preserved. It is clear that these were not weathered *in situ* because in most cases they are associated with blocks of hard undecomposed basalt. The conclusion is made that these bombs were exposed for some time on an older land surface following a previous explosive eruption.
(5) At least three different types of basalt distinct from one another and from the final thin surface flows nearby, both as regards lithological character and chemical composition. In view of the slight variation found in thick basalt sheets in other areas these three types of basalt blocks are referred to different lava flows.

It is apparent, therefore, that the Cainozoic volcanoes in the vicinity of Lake Burrumbeet burst through a granitic basement, and at intervals built up at least four distinct basalt sheets and two distinct fragmental deposits. However, without further boring operations the chronological order of those not exposed at the surface cannot be determined. (Figs. 6, 7.)

Description of the Basalts

Included block I (Analysis I, Table 15) is a relatively coarse-grained olivine basalt with doleritic and sub-ophitic texture. It closely resembles the top rock at Ballarat West both in hand specimen and under the microscope. Included block II (Analysis II) is an extremely dense and fine-grained basalt, dark grey-brown in colour. The thin section shows plagioclase laths with good fluidal arrangement, minute grains of augite and cubes of magnetite, and a few small phenocrysts of olivine up to 0·7 mm. in length and partly altered to green serpentine. Block III (Analysis III) is also a fine-grained olivine basalt. The texture is pilotaxitic and fluidal, and there are numerous microphenocrysts of olivine, partly iddingsitized. The hand specimen is dense and bluish-grey in colour.

The surface basalt forming the north cliff of the lake, and also the thin surface flow at Mt. Callender, are fine-grained light grey rocks showing occasional small

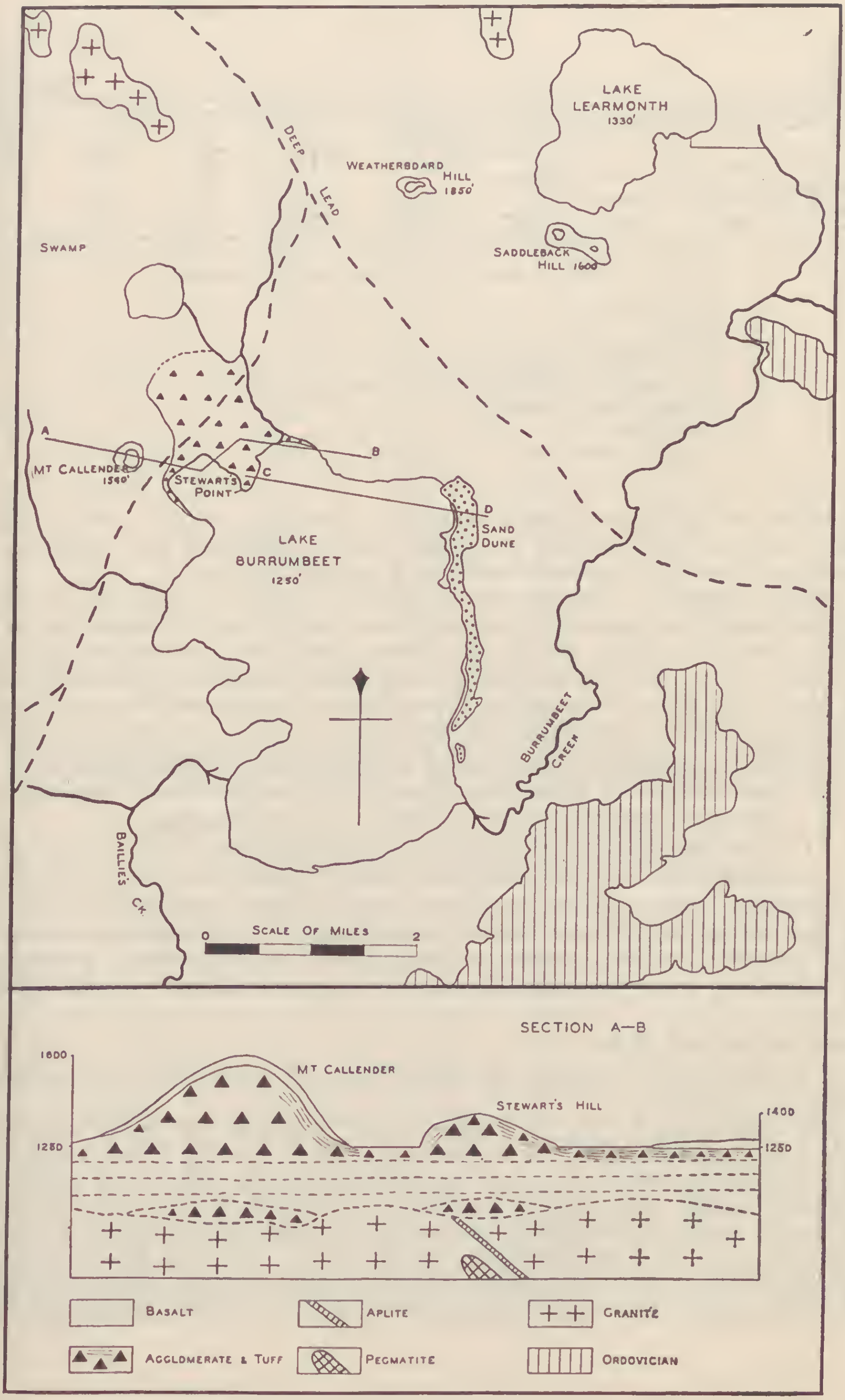


Fig. 6.—Geological map of section of the Burrumbeet area.

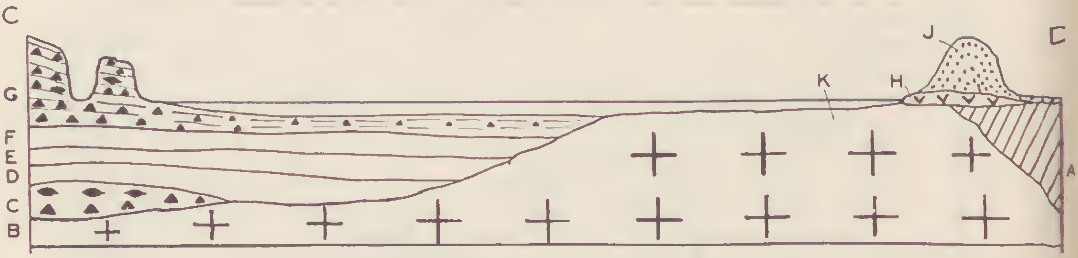


FIG. 7.—Sketch section CD across Lake Burrumbeet.

A. Ordovician.
B. Granite.
C. Earlier agglomerate with volcanic bombs.
D, E, F. Earlier basalt flows.
G. Agglomerate and tuff, with older volcanic bombs.
H. Weatherboard Hill basalt.
J. Sand dune.
K. Possible granitic lake bed in places.

phenocrysts of plagioclase in hand specimens. The thin sections resemble that of ejected block II, but there are two generations of plagioclase and augite, giving a few small phenocrysts of these minerals in addition to olivine.

Chemical analyses of the basalts are given in Table 15. They are all olivine andesine basalts, the plagioclase ranging from Ab_{64} to Ab_{52}. Comparison of the analyses reveals variation of the same kind as that found in the basalts of the Warrenheip area, that is, principally an antipathetic variation of the oxides MgO and Al_2O_3. Thus, similar trends of differentiation and contamination in the magma cupola are indicated in this area also, namely:

(1) Early crystallization and sinking of olivine and pyroxene crystals.
(2) Concentration of felspar constituents in the upper levels as a result of convection currents and the sinking of Fe-Mg minerals.
(3) Extraction of felspar constituents from the granitic throat of the volcano, making all the basalts alkaline by contamination.

The effect of these processes is most evident in the composition of the final lava flows from Mt. Callender and Weatherboard Hill. These two analyses, IV and V, are very similar, having low MgO content but high Al_2O_3, consequently both rocks have relatively small amounts of Fe-Mg minerals, but abundant felspars.

Details of the Tuff Beds

T. S. Hart (1901) described the tuffs and their included blocks in considerable detail.

Points of eruption: The very large blocks of granite and basalt set free by wave action are restricted to a stretch about 400 yards long of the rocky beach running north-east from Stuart's Point. This suggests a long narrow north-south vent here, distinct from Stuart's Hill a quarter of a mile to the west. The latter was clearly the source of most of the tuff because the beds dip gently to the east and south away from the hill parallel to its slopes. Mt. Callender was another explosive vent as shown by the easterly dip of the tuffs in the cliff section south-west of Callender Bay. Hart concluded that there were several explosive vents

TABLE 15

	I	II	III	IV	V
SiO_2	50.26	46.69	47.55	49.35	49.34
Al_2O_3	14.80	16.02	15.32	16.10	19.33
Fe_2O_3	4.20	2.02	6.60	4.13	1.85
FeO	7.18	8.93	5.94	7.94	7.92
MgO	7.22	7.58	6.64	4.90	4.28
CaO	8.41	8.31	8.69	7.06	6.94
Na_2O	3.26	3.16	3.36	4.12	4.16
K_2O	1.02	1.30	1.52	1.71	1.51
TiO_2	2.23	3.48	3.01	3.02	3.24
P_2O_5	.37	.42	.57	.34	.32
H_2O+	.72	1.73	.65	.65	.98
H_2O-	.50	.54	.56	.57	.49
Total ..	100.17	100.18	100.41	99.89	100.36
Plagioclase	Ab 56	Ab 52.5	Ab 57.5	Ab 64	Ab 56
Q	.43	—	—	—	—
Or	6.06	7.69	8.99	10.10	8.94
Ab	27.55	26.73	28.40	34.82	35.15
An	22.71	25.64	22.19	20.35	29.56
Di	13.33	10.42	13.49	9.99	2.40
Hy	17.74	1.46	6.57	3.70	2.88
Ol	—	15.53	2.99	7.27	10.48
Mag	6.09	2.93	9.57	5.99	2.68
Il	4.24	6.61	5.72	5.74	6.15
Ap	.81	.92	1.24	.75	.70
Total ..	98.96	97.93	99.16	98.71	98.94

I. Coarse grained andesine basalt block, type I., in the Burrumbeet agglomerate. *Analyst:* H. Yates.
II. Fine grained olivine andesine basalt block, type II., in the Burrumbeet agglomerate. *Analyst:* H. Yates.
III. Fine grained olivine andesine basalt block, type III., in the Burrumbeet agglomerate. *Analyst:* H. Yates.
IV. Olivine andesine basalt, resting on tuff and forming the low cliff, north shore of Lake Burrumbeet. *Analyst:* H. Yates.
V. Olivine andesine basalt, resting on tuff at Mt. Callender. *Analyst:* H. Yates.

in the area, but considered that the main one was in Callender Bay itself, which later subsided. This explanation is not accepted by the present writer.

Structures: The tuffs generally have good lamination, prevalent cross bedding, and local small indented basin structures due to the weight of larger blocks in the fine-grained unconsolidated deposit. These features are similar to those in the tuffs at Lake Purrumbete near Camperdown, described and figured by Hills (1940), and they suggest that most of the tuff at Burrumbeet was formed as "mud flows" from the two main points of eruption, Stuart's Hill and Mt. Callender. Lamination is practically absent in the vicinity of the coarse agglomerate north of Stuart's Point, due, no doubt, to rapid accumulation of the large blocks near this vent. Further north in this cliff section the lamination appears horizontal because the dip here is towards the east. The height of the cliff diminishes to nil at its northern end, due to distance from the main vent, Stuart's Hill, and to erosion by the small creek which enters the lake east of "Stuart's Hotel". To the east of this creek the tuffs pass beneath the thin edge of the final basalt sheet which forms the northern cliff of the lake. The writer has excavated to a depth of several feet in the soft tuff beneath the basalt here. It is finer- and more even-grained than in Stuart's cliff, suggesting that away from the points of eruption the smaller ejected fragments were sorted in lake water more extensive than the present lake.

In addition to the volcanic bombs and blocks of basalt and granite described above, the tuff beds contain a considerable proportion of small angular quartz grains, fragments of basalt and granite, and also occasional grains of fresh felspar and biotite, the whole being set in a brown ferruginous and clayey matrix. The minerals were obviously brought to the surface by volcanic explosion through the basement granite whose surface was in a decomposed condition. Rosiwal measurements from thin sections show that the small quartz grains amount to approximately ten per cent of the tuff in the northern part of Stuart's cliff.

As stated above, no final lava flow issued from the Stuart's Hill vent. However, a small amount of magma was ejected with the fragmental materials and solidified rapidly, forming small grains of tachylite, which is found in the massive tuff on the north-west side of Stuart's Point. The tachylite is black and resinous in hand specimens, but in the thin section it is pale green and isotropic, and shows flow lines in places. The theory of a pyroclastic origin for these fragmental beds at Lake Burrumbeet is supported by definite evidence of vulcanicity in the area, in the form of basalt sheets both above and below, also by the limited number of rock types found as fragments, namely granite, basalt and volcanic bombs, all of which could have been brought up from sub-surface formations, as explained. The possibility of a true sedimentary origin is discounted because of complete absence of fragments rounded by water action.

7. Basalts and Tuff at Smeaton

A great amount of boring was done by the Department of Mines and mining companies in the rich Smeaton alluvial field, to determine the course of the Berry Lead and its tributaries. The writer considered that study of the recorded specimens from a typical bore in this area might yield interesting information concerning the variation of composition in co-magmatic basalt sheets. Bore No. 151, drilled in 1906, was selected because the core specimens preserved are numerous and are numbered in sequence (Table 16). In addition, the depth of each specimen is

Table 16

Details of Berry Consols Extended D.D. Bore No. 151

Rocks pierced	Depth where struck	Thickness	Thickness of basalt sheets	Number of flow	Basalt cores preserved
Clay	0′ 0″	3′ 0″	—	—	—
Basalt gravel	3′ 0″	21′ 0″	—	—	—
Basaltic clay	24′ 0″	12′ 0″ }	13′ 0″	5	3
Basalt boulders ..	36′ 0″	1′ 0″ }			
Basalt	37′ 0″	110′ 0″	110′ 0″	4	4
Red clay ..	147′ 0″	8′ 0″ }	51′ 6″	3	9
Basalt	155′ 0″	43′ 6″ }			
Decomposed basalt ..	198′ 6″	16′ 6″ }	48′ 6″	2	11
Basalt	215′ 0″	32′ 0″ }			
Red and brown clays ..	247′ 0″	36′ 0″ }	82′ 0″	1	13
Vesicular basalt ..	283′ 0″	34′ 0″ }			
Hard grey basalt ..	317′ 0″	2′ 0″ }			
Clays	319′ 0″	7′ 0″	—	—	—
Sandy clay	326′ 0″	14′ 0″	—	—	—
Drift	340′ 0″	8′ 0″	—	—	—
Sandstone bedrock ..	348′ 0″	—	—	—	—

recorded (Table 17). The site of this bore was on the Berry Consols Extended lease, in the vicinity of McRorie's Hill.

Gregory (1903), after detailed examination of bore records to that date, showed that the basalts pierced in the Berry Consols Extended bores probably did not all originate from the same point of eruption, but that separate lava sheets from McRorie's Hill, Woodhouse Hill, Clover Hill and Mt. Moorookyle converged towards a depressed area along this part of the course of the Berry Lead. He described the deep so-called "hydrothermal deposits" in which several of the Mines Department bores were abandoned beneath the basalts as lake beds, but decided against the barrier lake, crater lake and volcanic explosion theories of the origin of the lake. He also concluded that the subsidence probably accompanied the first outbreak of vulcanicity at the McRorie's Hill vent and preceded the lava flows from the other vents in the area.

TABLE 17

Description of Core Specimens Preserved

No. of core Specimen	Depth	No. of flow	No. of Chem. Analysis	Macroscopical Features	Microscopical Features
3	36′ 0″	5	V	Dense, hard brown basalt	Porphyritic olivine andesine basalt with black glassy base
4	63′ 0″	4	IV	Vesicular blue basalt	Coarse ophitic olivine labradorite basalt
9	197′ 0″	3	III	Dense dark brown rock	Acid-andesine iddingsite augite trachy basalt
11	233′ 0″	2	II	Dense, light grey rock with occasional phenocrysts of olivine	Olivine andesine basalt with two generations of olivine. Fine-grained holocrystalline base
13 14	295′ 0″ 307′ 0″ }	1	I	Vesicular blue rock	Sub-ophitic labradorite basalt

It is difficult to imagine such a localized depression taking place, and in view of the fact that some of the bores were not bottomed at considerable depths in the "hydrothermal deposits" the present writer favours the theory of volcanic explosion along the course of the old river, followed by settling of the fragmental materials and small amounts of lava within the vent as the result of extensive water action. From Gregory's description of the "hydrothermal deposits" it would seem that they were partly sedimentary and partly pyroclastic in origin. Bore No. 151 did not penetrtae these basal deposits, but the core specimen No. 1 described as "basalt gravel" which was met at 3 ft. from the surface and penetrated for 21 ft. resembles basaltic tuff, and indicates that the final volcanic action in this area was also of the explosive type. The basalt core specimens from bore No. 151 are, no doubt, comagmatic, and may be considered as a series except for the possibility that the different sheets were extruded from neighbouring cupolas of varying compositions. Study of the chemical analyses (Table 18) shows that the rocks are andesine and labradorite basalts. Variation of the important oxides SiO_2 and MgO from flow to flow is considerable, and similar to that found in other series described above. The alkalis, however, vary in a different manner. In most other cases the combined alkalis were either uniformly low or uniformly high, but in the Berry Consols Extended series the total is low in two of the sheets (1, 4) while in the other three it is moderately high.

No certain conclusions can be made from these observations, but it is probable that this type of variation is due to extrusion from several cupolas in which variable convection differentiation had produced different magma compositions. It is also possible that the several vents passed through two different types of basement rocks with resultant variable contamination. The hornblende granodiorite encoun-

TABLE 18

No. of core specimen ..	13	11	9	4	3	
Depth	295′	233′	197′	63′	36′	
No. of Flow	1	2	3	4	5	
No. of Analysis ..	I	II	III	IV	V	VI
SiO_2	50.33	46.45	49.92	48.83	50.80	51.41
Al_2O_3	14.50	14.67	14.21	17.03	14.97	14.78
Fe_2O_3	1.69	1.40	6.59	3.81	1.90	2.20
FeO	8.78	9.37	5.08	6.70	7.13	8.42
MgO	4.18	8.87	5.18	6.97	5.99	6.93
CaO	9.03	7.58	7.96	9.36	9.22	8.30
Na_2O	2.84	3.18	3.74	2.80	3.32	3.70
K_2O	.70	1.52	1.46	.64	1.10	.89
TiO_2	2.30	3.28	2.57	1.86	2.42	1.86
P_2O_5	.32	.63	.49	.29	.34	.30
H_2O-	.88	.69	1.42	1.06	.31	.58
Loss on ignition ..	5.03	2.35	1.48	.97	2.71	.85
Total ..	100.58	99.99	100.10	100.32	100.21	100.24
Composition of plagioclase	Ab 51	Ab 60	Ab 65	Ab 45	Ab 57	Ab 61
Q	5.37	—	3.19	.33	.61	—
Or	4.15	8.99	8 64	3.89	6.51	5.27
Ab	24.00	26.82	31.62	23.67	28.06	31.44
An	24.72	21.16	17.67	31.93	22.66	20.97
Ne	—	.05	—	—	—	—
Di	14 93	9.98	14.50	10.13	16.91	14.87
Hy	13.97	—	6.24	18.65	14.34	14.08
Ol	—	20.24	—	—	—	4.78
Mg	2.45	2.03	8.92	5.52	2.76	3.19
Hem	—	—	.43	—	—	—
Il	4.37	6.24	4.89	3.54	4.60	3.54
Ap	.70	1.38	1.07	.63	.75	.65
Total ..	95.64	96.89	97.17	98.29	97.20	98.79

I. V. Smeaton Basalts. *Analyst:* H. Yates.
VI. Olivine—andesine basalt, Piggbreet. *Analyst:* H. Yates.

tered in the workings was described as a large dyke. It certainly indicates the existence of an unexposed granitic batholith.

8. Differentiation

The marked chemical difference between the basalts of Ballarat West and those of most other areas described calls for petrographical explanation. It is more correct to say that in most areas the basalts are abnormally alkaline and high in Al_2O_3, than that those of Ballarat West are abnormally low in alkalis. Practically without exception these alkaline basalts are rich in olivine, and it is evident that the parent magma was of the olivine basalt type.

One theory to explain the recorded differences of composition in the comagmatic basalts is that the extrusions in Ballarat West are older than the others, and that in the interval differentiation in the magma reservoir tended to cause concentration of the felspar constituents in the upper levels, with the result that phenocrysts of andesine are common in the later extrusions from Mt. Rowan, Mt. Hollowback, Clarke's Hill, etc., while lime-free anorthoclase appears in the still younger rocks at Mt. Warrenheip. Unfortunately, there is no reliable evidence of the relative ages of the different lavas mentioned, on account of lack of contacts. A second theory is local cupola differentiation as advocated by Edwards (1935). This process may have operated in the majority of centres even before the extrusion of the Ballarat West basalts, so that the latter need not be the first-formed. It is further suggested that the trend of differentiation in the direction stated was assisted by partial solution and assimilation of felspars from the granitic rocks into which the basaltic cupolas and necks rose, thus causing cupola contamination (Fig. 8). In the basalt at Gong Gong quarry and also in some volcanic bombs at Mt. Warrenheip, granitic xenoliths have been found consisting mainly of quartz grains, and this suggests that the felspars had been extracted to some extent.

The effect of such contamination would be to increase the percentages of SiO_2, Al_2O_3 and alkalis in the basaltic magma. The theory is supported by the fact that in the Yendon, Burrumbeet and Warrenheip areas, where distinctly alkaline basalts were extruded, the basement rock is granite. Also, the vents at Clarke's Hill, Green Hill, Buninyong, Millbrook, Gordon and Egerton are situated close to the margin of the outcropping granite, so that granite surrounded the greater part of the necks of these Cainozoic volcanoes. At Smeaton the hornblende granodiorite, met in some of the workings, and described as a large dyke, may have had similar influence on the composition of the lava from certain vents while not affecting others. Though the total alkalis in the Ballarat West basalts are relatively low, they are higher than in normal olivine basalts, and a limited amount of contamination by granitic felspar probably took place as indicated by Fig. 8.

9. Basalts of Other Areas

Despite the considerable time spent in field work, and the number of chemical analyses made, it is felt that much similar work remains to be done. However, many of the bore cores which might be desired have not been preserved. The petrological collection of the Victorian Department of Mines, Melbourne, contains several interesting slides of basalts from the Clunes and Amherst area, but no chemical analyses are available. It would be desirable to have a record of the petrological characters of the many basalt flows from the Divide to Inglewood; also to investigate further, in other areas, the suggested effect of extrusion through

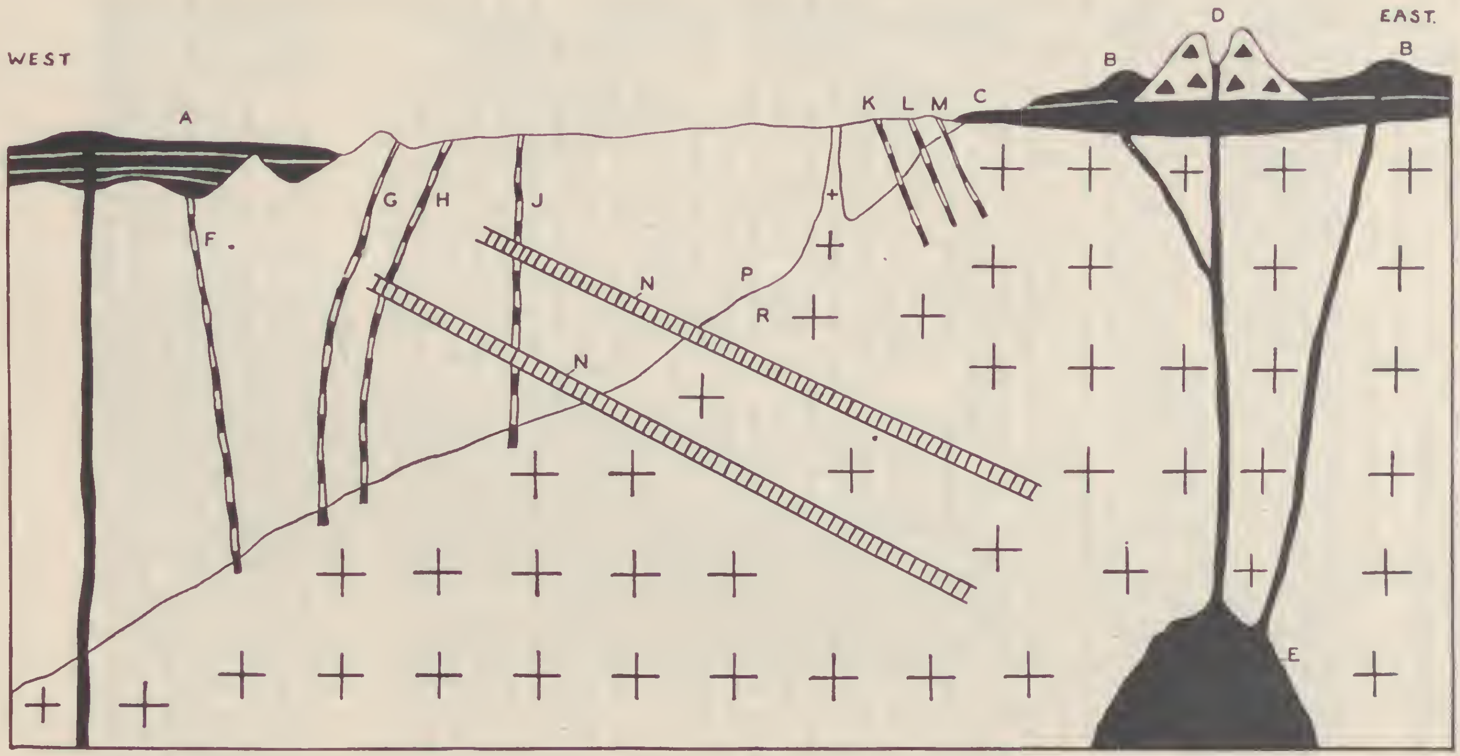


FIG. 8.—Sketch section from Ballarat West to Warrenheip illustrating contamination of basaltic magma by the granitic basement; also the dyke swarm associated with the granite.

A. Ballarat West basalts.
B. Warrenheip basalt.
C. Clarke's Hill basalt.
D. Mount Warrenheip.
E. Basaltic cupola.
F. Quartz-porphyry dyke.
G, H, J. Other acidic dykes.
K, L, M. Aplite dykes.
N. Basic dykes (lamprophyres).
P. Folded Ordovician.
R. Granite.

granitic basements. Some years ago the writer made sections and analyses of two basalt samples taken from the top and bottom of the 50 ft. cliff forming the eastern bank of Smythe's Creek at Piggoreet, in the hope of detecting some variation of composition. Although the section here exposed appears to consist of several thin basalt sheets, because numerous vesicular layers alternate with dense rock, there is but little variation of type from bottom to top, and the section is either a single flow or a series of thin flows from the same vent in rapid succession. Both these slides are olivine andesine basalt, but there is a difference of texture. The bottom layer is ophitic, while the top one has very fine, granular augite.

The two analyses are alomst identical and their average is shown in Table 18, No. VI. The specimens examined are from the final lava flow in this area. The earlier flows, which filled the Grand Trunk lead to the west, are not available for study.

10. Summary and Conclusions

The basalts in the Ballarat district are basic andesine to labradorite varieties, containing olivine. In the rocks of Ballarat West and some of those at Smeaton the combined alkalis have a relatively low total percentage ($3\frac{1}{2}$ to 4), but in most other areas the basalts are more alkaline (total $5\frac{1}{2}$ to $6\frac{1}{2}$) and therefore have a much greater proportion of felspars, while nepheline occasionally appears in the calculated mineral composition. This difference in the basalts is explained by cupola differentiation, involving concentration of the lighter felspar constituents in the upper levels of the cupolas before extrusion. Also this concentration was accentuated in some areas as a result of contamination of the magma by felspar constituents assimilated from granitic basements.

In all cases where a series of basalt sheets rest one upon the other, considerable difference of composition and texture was found from flow to flow. However, in general, practically no variation was found in the same flow at different depths at the same place. It is evident that processes of magmatic differentiation and contamination were active before extrusion and during inter-eruptive periods, but that differentiation was very limited in the lava after extrusion.

Part II.—The Granitic Rocks

The numerous outcrops of granitic rocks within a radius of 25 miles of Ballarat are grouped into three distinct areas, separated by Ordovician slates and sandstones. They are:

(1) The Gong Gong-Lal Lal area.
(2) The Beckworth-Learmonth-Burrumbeet area.
(3) The Mt. Emu-Mt. Bute area.

Other more distant granitic areas occur at Ingliston in the east, Mt. Cole, Lexton and Amphitheatre in the west and north-west, and at Craigie in the north. In the absence of evidence of exact age in most cases these granitic rocks are all provisionally correlated with the Upper Devonian Epoch of intrusion throughout Victoria.

Thus we may picture an extensive Upper Devonian granitic magma underlying the greater part of Victoria, and from this, cupolas of various sizes stoped to different heights before solidifying. Some of these granitic masses were exposed at the surface by erosion before the Permian Period, and most of the others by the Tertiary, because they have been covered by basalt flows. Study of the buried

Tertiary river systems shows that the granites in most cases had been considerably dissected by erosion, and when these valleys were filled with basaltic lava, only isolated granite outcrops remained within the boundaries of the original cupola.

Chemical, mineralogical and textural differences are found in the rocks of different cupolas, and explanation of these involves conjecture as to their underground extent.

In the Ballarat district it was found that the most alkaline rock types occur in the largest cupolas, which also generally rise to the greatest heights; examples are Mt. Cole, Mt. Emu and Mt. Beckworth granites. The Gong Gong, Ingliston and Craigie cupolas are composed of the very common Victorian rock type best described as biotite-adamellite, because they are neither true granites nor true granodiorites. The only true granodiorite found in the district is the biotite-hornblende-granodiorite outcropping as a small stock to the south of Amphitheatre, and it is suggested that this rises from a considerable depth, so that differentiation by convection was limited, and the rock has a composition corresponding to lower levels of the large cupolas, in the upper parts of which gravity and convection caused a concentration of the lighter felspars, orthoclase and microcline.

1. The Gong Gong-Lal Lal Cupola

This forms the basement rock of the Warrenheip plateau. It is now covered to a large extent by basalt, but outcrops at Gong Gong, Warrenheip railway station, Dunnstown, Buninyong East and Lal Lal.

On the Yarrowee Creek, half a mile west of the Gong Gong reservoir, the Ordovician contact rock is spotted micaceous sandstone. The rock type of this cupola is biotite adamellite (Analyses 1, 2, Table 19), and is medium- and even-

Table 19

	1	2	3	4	5	6	7	8	9	10	11
SiO_2 ..	70.22	68.99	71.57	76.96	76.31	71.16	76.22	73.76	74.01	73.98	65.94
Al_2O_3 ..	16.32	15.34	13.58	13.04	12.44	14.06	13.27	15.10	14.05	13.30	15.37
Fe_2O_3 ..	.42	1.00	1.18	.65	.70	2.88	.34	.64	1.80	.61	1.27
FeO ..	1.40	2.56	2.19	.25	.70	2.88	1.06	1.16	1.80	1.40	3.28
MgO ..	.78	1.48	1.07	.08	.22	.89	.13	.04	.45	.71	2.92
CaO ..	2.02	2.16	1.72	.33	.64	1.68	.51	.43	.66	1.56	4.18
Na_2O ..	3.86	3.37	2.79	3.54	2.38	3.16	3.74	3.56	3.10	4.96	3.60
K_2O ..	3.62	3.54	4.36	4.96	6.01	5.70	4.14	4.86	4.72	3.16	1.72
TiO_2 ..	.54	.45	.46	.07	—	.31	.13	.15	.21	.40	.62
P_2O_5 ..	.11	.13	.11	.02	—	.12	nd .05	nd .05	.06	.06	.11
H_2O+ .	.53	1.03	.69	.44	.42	.34	.25	.57	.58	.44	.84
H_2O-	Nil	.28	.11	.03	.24	.12	Nil	.14	.07	Nil	Nil
MnO ..	—	.11	.09	—	—	—	—	—	—	—	—
Total	99.82	100.44	100.21	100.37	99.36	100.54	99.84	100.17	99.65	100.68	99.85

		Location	*Analyst*
1.	Biotite adamellite	Gong Gong	H. Yates
2.	Idem	—	J. Clark
3.	Biotite adamellite	Ingliston	A. G. Hall
4.	Aplite	Gong Gong	H. Yates
5.	Pegmatite	Lal Lal	F. F. Field
6.	Porphyritic biotite granite	Mt. Beckworth	H. Yates
7.	Aplo-granite	Learmonth	H. Yates
8.	Two-mica granite ejected block	Burrumbeet	H. Yates
9.	Biotite granite	Mt. Bute	H. Yates
10.	Biotite granite	Mt. Cole	H. Yates
11.	Biotite-hornblende-granodiorite	Amphitheatre	H. Yates

grained at Gong Gong, but porphyritic in felspar at Lal Lal. At Warrenheip and Gong Gong the adamellite is traversed by thin north-south veins of aplite which generally dip easterly. The 8 in. vein exposed in the small quarry just south of the Melbourne road on Woodman's Hill passes locally into graphic pegmatite at the margin. At Kirk's reservoir, Gong Gong, the aplite veins are numerous and vary from ½ to 15 in. in thickness. They are quite close together, and most of them are approximately parallel. Is is clear that, after the upper part of the cupola had solidified as adamellite, it developed fairly regular tension gashes while cooling, and along these were intruded streams of the upper part of the remaining magma which had undergone considerable differentiation in the meantime. This explains the more acid and alkaline character of the aplite as compared with the adamellite, and also the paucity of biotite in the former. Along the bounding planes of the aplite and adamellite, and also along joint planes in the latter, grains of molybdenite, chalcopyrite and pyrite occur in places, as at Woodman's Hill. Obviously these were deposited from late magmatic emanations after the intrusion of the aplite.

At Lal Lal, approximately half a mile north-east of the Lal Lal Falls, a large mass of pegmatite occurs within the adamellite, and clearly some depth below the original top of the cupola. Although quarried for felspar many years ago, this rock cannot be traced far on the surface, and is probably an irregular lenticle or pipe. The pegmatite is cream coloured and coarse grained, and consists chiefly of quartz and orthoclase which are micrographically intergrown in places. Large thin plates of biotite occur in parts of the rock.

Baragwanath (*op. cit.*, pp. 54-56) described in some detail the numerous dyke rocks encountered during the mining at Ballarat and thin sections of many of them were made in the laboratories of the Department of Mines, Melbourne. He classified them into an acidic series with strike approximately north-south, and a basic series, mostly east-west. The former include quartz-porphyry, kaolinized felspar-porphyry and felsite, also a dioritic dyke in the Woah Hawp No. 1 mine. The basic series were described as lamprophyres and monchiquites chiefly, also "basaltic dykes" (dolerite) at Brown Hill and Magpie. However, their mineralogical constitution is indefinite in most of the slides, and chemical analyses have not been made. Baragwanath showed that the acidic series of dykes are of the same age as the auriferous quartz reefs but that the basic dykes are younger than the reefs and also younger than the cross-course faults whose fissures they occupy in some cases. It follows that the acidic dykes are of Upper Devonian age and co-magmatic with the adamellite, aplite and pegmatite, but that at least some of the basic dykes are Pliocene or Pleistocene and are magmatically related to the surface basalt sheets. This is probably true of the dolerite and monchiquite dykes, but possibly some or all of the lamprophyres are Upper Devonian and are to be correlated with the lamprophyres at Daylesford, Creswick, Maryborough and Talbot. If so, they complete a typical differentiated dyke swarm in the Ballarat area when studied in conjunction with the aplites, pegmatite, quartz-porphyry and the parent adamellite magma. This relation is illustrated by the section (Fig. 8).

The adamellite at Gong Gong and Lal Lal contains numerous dark xenoliths, generally rounded by partial assimilation. Their grainsize varies from medium and even in some, to fine and porphyritic in others. Thin sections show that these xenoliths are composed entirely of the same minerals as the adamellite itself, namely quartz, plagioclase and biotite. The felspars are quite fresh and the quartz grains show no signs of rounding by water action as would be expected if they had been constituents of sandstones. It is therefore concluded that the xenoliths are cognate and were freed by stoping of the early solidified upper margin of the cupola. The xenoliths are very numerous near the pegmatite mass at Lal Lal, and in their vicinity the adamellite contains large phenocrysts of poikilitic and crypto-perthitic soda orthoclase (Analysis 1, Table 20).

TABLE 20

	1	2	3	4	5
SiO_2	64.04	65.64	34.42	46.11	.38
Al_2O_3	20.10	19.43	25.84	39.54	—
Fe_2O_3	—	—	—	—	86.94
FeO	—	—	13.07	—	—
MnO	—	—	25.87	—	—
MgO	.05	.04	Nil	—	—
CaO	.26	.10	Nil	—	—
Na_2O	2.10	4.24	nd	—	—
K_2O	12.36	10.04	nd	—	—
TiO_2	—	—	.07	.48	—
P_2O_5	—	—	nd	—	—
H_2O+	.40	.20	nd	14.12	12.68 nd
H_2O-	—	—	nd		
Total ..	99.31	99.69	99.27	100.25	100.00

		Location	Analyst
1.	Soda orthoclase phenocrysts in adamellite	Lal Lal	H. Yates
2.	Soda orthoclase	Mt. Beckworth	H. Yates
3.	Spessartite garnet	Learmonth	H. Yates
4.	Kaolin "dyke"	Lal Lal	H. Yates
5.	Limonite	Lal Lal	H. Yates

In the flat areas of the Lal Lal swamps the adamellite near the surface has been decomposed, forming a mixture of kaolin and quartz grains. This clay was used for the manufacture of fire bricks and pottery about the beginning of the century and at the present time it is being produced again from an open-cut mine for use in the manufacture of paper at Ballarat. Other important deposits of kaolin occur as north-south dyke-like masses in the Ordovician rocks of the Mt. Doran ranges east of Lal Lal and also at Mt. Egerton to the north. These kaolin "dykes" are being mined by several different companies and approximately 2,000 tons are being produced annually. No solid rock was found even in the lower levels (150 to 200 ft.), and it is therefore clear that the kaolin was not formed by alteration of igneous rocks by meteoric solutions, but by thorough kaolinization of Upper Devonian felspathic dykes by late acidic emanations from the adamellite magma.

2. The Burrumbeet-Learmonth-Beckworth Cupola

Large outcrops of this rock, separated by basaltic plains, form the prominent rocky mountains Mt. Beckworth, Mt. Bolton and Mt. Misery, while the chief of the less prominent outcrops forms a hill one mile north-west of Lake Learmouth. Ejected blocks in the Burrumbeet tuff show that the same rock forms the basement there, and no doubt it was exposed on the early Cainozoic land surface. The characteristic rock type of this cupola, occurring at Mt. Beckworth and Mt. Bolton (Analysis 5, Table 19), is porphyritic biotite granite, the phenocrysts being pink orthoclase with Carlsbad twinning quite common. Many of the blocks at Lake Burrumbeet are of the same type, and some are traversed by thick veins of aplite and graphic pegmatite. It is evident that these blocks, and also those of fine-grained white two-mica granite, were broken from the upper levels of the cupola, because injected veins and lenses of aplite and pegmatite are numerous in the same granite outcropping at Mt. Beckworth and Learmonth. The occasional blocks of very coarse even-grained pegmatitic granite probably came from lower levels in the cupola where crystallization was uniformly slow.

FIG. 9.—Radial quartz-garnet intergrowth. × 13.

The rock north-west of Learmonth is pink aplo-granite of medium and even grainsize (Analysis 6, Table 19). It consists mainly of quartz and orthoclase, occasionally intergrown, with small quantities of biotite. Lenticular veins of coarse biotite pegmatite are numerous near the top of this outcrop, and at one place only the pegmatite contains crystals of black garnet, while in one of the numerous vughs in the pegmatite an interesting radial graphic intergrowth of garnet and quartz in approximately equal proportions was found (Fig. 9). The garnet is iron-bearing spessartite (Analysis 3, Table 20). No previous reference to such an intergrowth has been found. Andrews (1916) described garnet pipes in granite at Whipstick, N.S.W., and a massive garnet zone in the granite at Yetholme, N.S.W.; some quartz was associated with the garnet, but the two minerals were not intergrown. It is clear that at Learmonth the final pockets of magma were composed chiefly of quartz, and orthoclase molecules, because most of the pegmatite contains no biotite or garnet. A few of them contain large plates of biotite, and one only contains the manganese garnet. In these cases, therefore, the final magma pocket contained concentrations of iron and manganese, and the probable order of crystallization of the pegmatite minerals was: (1) biotite, (2) orthoclase and quartz, (3) garnet and quartz.

In the porphyritic granite on the north-west slope of Mt. Beckworth, near Clunes, a large flat dyke of coarse pegmatite occurs. Although somewhat irregular, it strikes approximately east-west and dips to the south. It is composed mainly of cream-coloured soda orthoclase (Analysis 2, Table 20), with some quartz in the form of large crystals and masses which can be easily separated from the felspar by hand picking. This felspar was tested and used to some extent by Mr. T. Trengrove in the Pottery Department of the School of Mines, Ballarat. It gives a very good quality glaze. Prior to 1914 it was mined by a German syndicate.

3. The Mt. Emu Cupola

The rock outcropping at Mt. Emu north-west of Skipton is a true biotite-granite, cream coloured, and containing abundant orthoclase. This main outcrop stands over 500 ft. above the surrounding basalt plains which separate it from less prominent outcrops to the north, east and west, including a large area in the parishes of Argyle and Mannibadar. Thus the pre-basaltic outcrop of this cupola was about 25 miles N.-S. by 8 miles E.-W. At Mt. Emu the granite contains numerous thin meridional lenticular masses of biotite-pegmatite, also thin veins of aplite and reef quartz. In the vicinity of Flagstaff Hill lookout, west of Linton, the marginal part of the granite has an aplitic texture. The specimen analysed from this cupola was taken from Mt. Bute, three miles south of Linton (Analysis 8, Table 19).

4. The Mt. Cole Cupola

Practically the whole area of this cupola outcrops as a large monadnock north-west of Beaufort, with smaller extensions to the north near Elmhurst, where the principal peak is Mt. Direction, and to the west forming Mt. Buangor, which is separated from the main mass by alluvium in the broad valley of the Wimmera River.

The typical rock, collected from the east and north-east margins of the cupola, is pink biotite granite in which the felspar is chiefly microcline (Analysis 9, Table 19).

5. The Lexton-Amphitheatre Stocks

Two small outcrops of granitic rock occur between Lexton and Amphitheatre, to the east of the Mt. Cole mass, and separated from it and from one another by Ordovician rocks, metamorphosed to a considerable degree. These rocks differ so much from the Mt. Cole granite that they are probably connected with it only at a great depth, descending as nearly vertical stocks. Analysis of the Amphitheatre specimen (No. 10, Table 19) shows it to be granodiorite. The femic minerals are biotite and hornblende, and the rock is medium- and even-grained and light grey in colour. The small stock forming "granite hill" four miles south of Lexton is composed of grey biotite adamellite.

References

Andrews, E. C., 1916. The Molybdenum Industry in N.S.W. *Min. Resources of N.S.W.*, 24.
Baragwanath, W., 1923. The Ballarat Goldfield. *Mem. Geol. Surv. Vic.*, 14.
Coulson, A., 1937. The Basalts of the Geelong District. *Proc. Roy. Soc. Vic.*, 51.
Edwards, A. B., 1935. Three Olivine Basalt-Trachyte Provinces and some theories of Petrogenesis. *Proc. Roy. Soc. Vic.*, 48.
———, 1938. The Tertiary Volcanic Rocks of Central Victoria. Reprinted from *Q.J.G.S.*

Edwards, A. B., 1942. Differentiation of the Dolerites of Tasmania. *Journal of Geology.*
————, 1945. The Composition of Victorian Brown Coals. *Proc. Aust. Inst. Min. and Met.*
Gregory, J. W. (1903). *Geography of Victoria.*
Hart, T. S., 1901. The Tuffs of Lake Burrumbeet. *Vic. Nat.*
Herman, H., 1922. The Brown Coals of Victoria. *Bull. Geol. Surv. Vic.*, 45.
Hills, E. S., 1940. *The Physiography of Victoria.*
Hunter, S., 1909. The Deep Leads of Victoria. *Mem. Geol. Surv. Vic.*, 7: Pl. IV.
Lidgey, E., 1894. Report on Ballarat East Goldfield. *Special Report Mines Dept., Melb.*
Mahoney, D. J., 1928. Volcanic Minerals. *Proc. Roy. Soc. Vic.*, 40.
Watson, J. C., 1925. Fossil Resins from Yallourn, Allendale and Lal Lal. *Rec. Geol. Surv. Vic.*, IV.